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13. ABSTRACT (Maximum 200 words)

This report results from a contract tasking State Research Center of Russia as follows: A monograph entitled 'Technological Environmental Oscillations of Low Frequency (below 20 Hz) as a Risk Factor for Human Health: Hygienic, Medical, Biological, and Pathogenic Mechanisms)' will be prepared. This monograph will summarize and review in English the extensive research on this topic from the period of the Former Soviet Union to the present. The detailed monograph will be in a format suitable for publication as an Air Force Research Laboratory Technical Report. Also, a summary of the monograph will be prepared in a format suitable for publication in an English language Western scientific journal.

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BIOLOGICAL EFFECTS OF LOW FREQUENCY ACOUSTIC OSCILLATIONS AND THEIR HYGIENIC REGULATION

(MONOGRAPH ABSTRACT)

BIOLOGICAL EFFECTS OF LOW FREQUENCY ACOUSTIC OSCILLATIONS AND THEIR HYGIENIC REGULATION

Basic physical concepts

According to the adopted classification, the infrasound is defined as sound oscillations of frequencies below 20 Hz (some researchers sometimes note the upper limit of 16 Hz). The adopted subdivision is determined by the peculiarities of the human hearing apparatus perceptiveness of the specific frequency range only. The limits of the hearing are conditional. It is known that they depend on the individual sensitivity of the sound perceptive apparatus and age dependent peculiarities of the human hearing function. Lower infrasound frequency is not specified; at present it is investigated to 0.001 Hz, i.e. infrasound range covers ~ 15 octaves.

The infrasound or low frequency oscillations of the infrasound band (< 20 Hz) are widely disseminated in the environment. The infrasound is the persistent factor of noises and vibrations naturally occurred due to the turbulence of fluids and gases, at sea storms, tide waves, air flow above mountain areas, earthquakes, volcano eruptions, bolide explosions, polar auroras, strong thunderstorms and seismic events.

Though the physical nature of the infrasound is similar to that for sound waves of any frequency bands, it was already noted that it has a number of peculiarities giving the long distance propagation and far distance exposure abilities. These peculiarities are basically caused by low frequencies and large wavelengths. In case of infrasound frequencies, wavelengths in the air are 17 m to 34 km, 75 m to 150 km in the water, and 150 m to 300 km in the ground surface. The infrasound attenuation in the environment occurs at the distance from the source and is caused by the energy absorption in the atmosphere for less than 1%. It is supposed that average constant infrasound background is specific to the sound pressure of 0.001-0.0035 Pa (35-40 dB) in the frequency band of 1-0.02 Hz.

Hurricanes and oceanic storms are powerful infrasound sources. They occur due the turbulence of fluid and gas flows occurred at sea storms, tide waves (tsunami) (up to 140-145 dB, "linear scale"), air movements above the mountain areas.

The seismic activity is correlated to the solar activity. It is very probable, that the same solar activity correlation exists for infrasound noise intensification. Infrasound signals generated by polar aurora are tightly correlated to the solar activity. The polar aurora creates LSP of ~ 100-110 dB "linear scale". Magnet storms are accompanied by acoustic infrasound storm with 100% probability and its signals cover the band of 0.05-0.01 Hz.

The infrasound pressure was detected in the aircraft pathways, inside automobiles, trains and vessels, during the operation of the vessel engines, compressors, vibration instruments, fans, air conditioners, powerful turbines of diesel electric supplies, gas turbine installations, Martin furnaces.

It is established that infrasound of high intensity (>120 dB) is able to inflict health harm. Infrasound vibrations are more harmful because of dangerous resonance phenomena in some organs. The powerful infrasound can destroy or damage constructions and equipment too. At the same time, the infrasound (due to the long distance propagation) can be usefully applied to investigate ocean, upper atmosphere; the eruption or explosion site can be infrasound detected, when solving different problems of communication and detection. Infrasound waves emitted in case of underwater eruptions can predict tsunami.

The infrasound research is most frequently elaborated applying the explosion to generate infrasound, because emitters of routine type are high sized and low effective; they also have large reactive power. To receive infrasound, they use microphones, hydrophones and geophones, which design and amplifier electronics are adjusted to large amplitudes,

low frequencies and large input resistance of the detecting element. Specialized low frequency receivers of electronic-chemical, thermistor and optical type are also used.

Natural and artificial (man-made) sources of the infrasound and low frequency acoustic oscillations

The range of natural and artificial (man-made) sources of the infrasound and low frequency acoustic oscillations is $2 \cdot 10^{-5}$ Pa to $\approx 10^5$ Pa. Sound pressure levels are 0 dB to $\approx$ 194 dB.

The sound pressure level of $\approx 10^5$ Pa was recorded near missile engines. Common life noise is usually less than 100-110 dB. Basic value of the sound pressure ($P_o = 2 \cdot 10^{-5}$ Pa) is the limit of aural perception of human and average pain threshold is 120-125 dB.

The development of modern technologies, transportation and improvements of technological processes and equipment accompanied by the increase of power and sizes of machines has resulted to the significant increase of infrasound components of the environment and their intensity growth. These components are generated at the time of reciprocating movement of parts of different mechanisms and inside operated installations: blast furnaces, diesel motors, forge presses, reactors. Low frequency acoustic oscillations are also generated by the aircraft, space missiles, artillery shots and such powerful sources like nuclear explosions. The option to detect nuclear explosions at far distances using long distance propagation in the atmosphere was the start point of the development of the infrasound measurements and theoretical studies on infrasound radiation propagation.

Inside the helicopter, the level is 110-120 dB at < 20 Hz. At the time of the supersonic barrier crossing, the jet results to the shock wave of maximal spectral density at 1-10 Hz. The infrasound pressure in jet trajectories (~140 dB), inside railroad trains and sea vessels, near compressors, vibration units, fans, air conditioners, power turbines of the electric power plants, and Martin furnaces was found. In such case the maximal sound pressure levels (SPLs) are found at octaval bands of average geometric frequencies of 8, 16 and 31.5 Hz; most maximal levels are 90 to 118 dB; so, that in case of sound levels of 70 to 100 dB "A scale" correspond to infrasound expressiveness (dB"Lin" - dB"A" difference) is 5 to 42 dB.

Infrasound oscillations are generated in case of oscillations of large surfaces and powerful aerodynamic processes in the elastic media. Particularly, machines named above have maximal sound pressure levels of 100-135 dB (Table 1).

Table 1 – Workplace classification for transport means and technological equipment according to noise characteristics of the infrasound band (from Izmerov N.F. et al, 1998)

Spectrum character	Octaval bands with maximal levels of the sound pressure	Machines and equipment
Infrasound	2, 4, 8, 16 Hz; 82-133 dB	Automobiles, blast and oxygen converting furnaces, river and sea vessels, trains, compressors
Low frequency infrasound -	2-125 Hz; 84-112 dB	Martin furnaces, some kinds of transport vehicles, self-propelled and semi-stationary machines
Low frequency	31.5, 63, 125 Hz; 84-116 dB	Electric arc furnaces, drive trucks, caterpillar tractors, port cranes, turbine installations, loading trucks, dredges

Biological effects of infrasound and low frequency oscillations

Systematic studies devoted to low frequency acoustic effects were started in 1970^{th} – 1980^{th}. Basic causes of this interest were the absence of regulating documents and new publications indicated to the high biological effectiveness of the infrasound.

The majority of these studies were represented (1973) and published (1974) in the Paris International Colloquium on infrasound health effects; L. Pimonow has published the monograph (1976) entitled "Infrasound", which monograph, together with Russian researchers (Andreeva-Galanina E.Tc. Karpova N.I., Suvorov G.A., Malyshev E.N. and others), was the basis and start point of Russian research. At present time, N.F. Izmerov et al (1998) have published the monograph reflecting the viewpoint of Russian researchers.

These studies have indicated to the fact that 110 dB to 174 dB infrasound is able to induce unpleasant subjective reactions: nausea, chest vibration, stomach pains, headaches, giddiness, unexplained fear, swallowing and breath complications, spatial disorientation, tympanic oscillation and tympanic massage sensation (Andreeva-Galanina E.Tc., 1970; Karpova N.I. et al, 1973; Reutov O.V., 1978; Evdokimova I.B., Shypack E.Yu., 1979; Gavreau V., 1966; Pimonow L., 1976; von Gierke H.E., Parker D.E., 1976; Tempest W., 1976).

Russian and foreign researchers have advanced the infrasound health effects issue. The expressed unfavorable health effects of infrasound were established, essentially in psycho-emotional area; they affect the workability, cardiovascular and endocrine systems, cochlear vestibular apparatus. It should be noted that attitudes regarding infrasound health effects are ambiguous. Some researchers indicate that infrasound is very health harmful factor even able to induce the fatal outcome in some conditions. Other authors are more constrained.

The accumulated data on the infrasound health effects have given the opportunity to make the conditional subdivision of its effects from fatal ones to very mild effects with unclear response. The first attempt of such subdivision into four groups was tried at 1973 Paris Colloquium (Pimonow L, 1974; Johnson D.L, 1974).

These groups of infrasound health effects, L. Pimonow (1973, 1976), are specified as follows:

I – infrasound of > 185 dB, which is of fatal danger (the variable pressure of such levels can induce pulmonary alveolar rupture);

II – infrasound of 140 dB to 172 dB, which 2 minute exposure is tolerable for healthy human;

III – infrasound of 120 dB to 140 dB, which is able to induce mild physical disturbances and fatigue in case of many hour exposures;

IV – infrasound of < 120 dB, which is not health harmful if its exposure time is less than several minutes; reactions of the long-time exposure are the subject for future studies.

Similar grouping are provided by A. Stan (1974) as follows: 180-200 dB is the fatal danger range; 150-180 dB is the range of clear dangerous effects; 140-150 dB at 0.1 Hz and 105-150 dB at 63 Hz is the range of dangerous effects; < 105 dB at 63 Hz and < 143 dB at 0.1 Hz are the ranges of the significant effect absence.

Thus, the averaged border of the infrasound health effect threshold is in the area of 112 dB at 31.5 Hz up to 140-143 dB at 0.1 Hz. A. Stan (1974) has proposed the interpretation of infrasound effect ranges: 180-200 dB (fatal danger), 150-180 dB (dangerous health effects), 140-150 dB at 0.1 Hz and 105-150 dB at 63 Hz (harmful effect range) and –3 dB at 0.1 Hz (absent effect range). Thus, the averaged threshold of the infrasound health effects is 112 dB (31.5 Hz) to 140-143 dB (0.1 Hz).

Before the analyzing literature data regarding infrasound health effects, it is necessary to consider experimental equipment applied to generate infrasound oscillations.

The majority of published studies were elaborated applying dynamic pressure chambers (DPC). These are different hermetic chambers with rigid walls. Infrasound sources are either electric loud speakers or rigid membranes moved by different driving mechanisms. These membranes of loud speaker membranes make reciprocating shifts with rate of less than 20 Hz, which results to sinusoid change of the air pressure inside the chamber. It should be noted that DPC do not have the sound wave propagation but only pressure oscillations, which imitate infrasound exposure (Pimonow L., 1974). DPC application is considered to be applicable to reveal infrasound physiological effects; it is economically positive and easy to be designed (Malyshev E.N., 1979).

To directly expose examinee ears, some researchers (Evans M., 1972; Leventhall H.G., 1974 and others) have designed specialized infrasound headphones (so-called aural way of infrasound exposure). These headphones were tightly attached to examinee ears. Because of the elastic layer, only infrasound air oscillations have affected ears without vibration interference. However, such way results to the exposure of ears only, which is not adequate to environmental infrasound exposure.

The application of DPC, headphones and other appliances is related to significant technical difficulties of formed acoustic field generation. These difficulties consist in the fact that formed acoustic field is present at distance of the wavelength. For infrasound this distance is tens or even hundreds of meters. Taking into account the low source efficiency and spherical character of acoustic oscillation propagation, the energy portion is very low in the formed field. Therefore, it is necessary to apply very powerful sources to get significant infrasound levels, which is difficult to realize in practice.

To get real infrasound waves, V. Gavreau has designed and constructed the infrasound emitter of the enlarged police whistle type, which size was ~ 1.5 m. The air supply was provided by the compressor. At present time, the units specific to larger infrasound SPL are available. These are emitters of directed effect. One of such source described in literature consists of a number of powerful infrasound loud speakers placed at half wavelength distances. To get the sound "beam" the even dynamics are provided one phase signal and the odd ones are provided the alternative phase signal. Because of summation of sound waves, the resulting sound wave has almost plane front.

Early published health effects of the infrasound are generalized by Table 2.

The literature data on industrial infrasound effects in human and organism are sparse. These studies have indicated to the fact that 110 dB to 174 dB infrasound is able to induce unpleasant subjective reactions: nausea, chest vibration, stomach pains, headaches, giddiness, unexplained fear, swallowing and breath complications, spatial disorientation, tympanic oscillation and tympanic massage sensation (Andreeva-Galanina E. Tc., 1970; Karpova N.I. et al, 1973; Reutov O.V., 1978; Evdokimova I.B., Shypack E.Yu., 1979; Gavreau V., 1966; Pimonow L., 1976; von Gierke H.E., Parker D.E., 1976; Tempest W., 1976).

Table 2 – Infrasound human health effects

Author(s)	Sound pressure level, frequency, exposure time	Health effects
Slarve R.N., Johnson D., 1975	144 dB; 1-20 Hz; 6 min	Audiometry has not revealed significant shifts for aural analyzer in males.
Borredon P., Nathi L., 1974	130 dB; 7,5 Hz; 50 min	Some increase of diastolic pressure in males from 61.9 to 63.2 mm.
Karpova N.I. et al 1972	136 dB; 10 Hz; 15 min	Pulse rate increase and minimal AD increase (for 7-11 mm) in males.
Reutov O.V., Erofeev N.P., 1976	135 dB; 5 и 10 Hz; 15 min	Heart automatism disorder with peculiar change of cardiac constrictions
von Gierke H., 1974	154 dB; 1-100 Hz;	Unpleasant sensations in the ear have risen from 145 dB; 150-153 dB was the limit threshold of voluntary tolerance. At these levels, the scratching sensation and outside body presence sensation have occurred in the throat; caught attacks have started and some males had nausea feeling.
Nixon Ch., 1974	> 125 dB; 1-20 Hz; 8 min	125 dB and more results to tympanic massage coinciding to the oscillation frequency. > 140 dB has induced pain sensation. At 10 Hz, the pain threshold was ~ 150 dB. The pain threshold is increased for the decreasing frequency.
Karpova N.I. et al 1972	136 dB; 10 Hz	Significant change of the peripheral blood circulation (20-22% blood flow increase if compared to initial data).
Evans M., Tempest W., 1972	140 dB; 7 Hz	7 Hz frequency is most "effective" for vestibular apparatus; this frequency is sensible for semicircle channels and otolith system detecting the gravity.
Prazak B., 1974	80-152 dB; 4 Hz	At 4 Hz the tolerance threshold is 87 dB and pain threshold is ~152 dB.
Sherer, J., 1973	140-170 dB; 3, 15 and 100 Hz;	The pain threshold was found to be as follows: 170 dB for static pressure; 165 dB at 3 Hz; 140 dB at 15 Hz and 120 dB at 100 Hz.
Leventhall H., 1974	126 dB; 2 – 20 Hz	Subjective reaction studies in 6 volunteers have indicated to the average reaction time change from 0.414 s to 0.430 s in case of the infrasound exposure only. The "arrow surveillance" test was found to get 10% productivity loss in case of the noise or alcohol.
Mohr G. et al, 1965	119 – 144 dB; <22 Hz; 3 min	Subjective body vibration. At 144 dB, half of examinees had breath rate increase. All examinees had transient shift of the aural threshold (>120 dB).

Alford B. et al, 1966	Up to 154 dB; 1 – 100 Hz	150 dB is tolerable for heart rhythm, aural threshold, vision power, spatial orientation changes.
Gavreau V., 1968	7 Hz	Low intensive 7 Hz infrasound induces nausea and fatigue at hour 2 of the exposure of intellectual operator.
Sharp M., 1971	Low frequency noise during spaceship launch	Low frequency noise and vibration result to discomfort, irritation, nausea, abdominal and vertebral pains, obstructed breath and other unpleasant sensations, which pre-cause anxiety and fear.
Johnson D., 1974	< 144 dB; 1 – 30 Hz	Voice modulation and middle ear pressure sensation in case of > 132 dB.
Leventhall H., 1974	140 dB; 2 Hz	Mild nausea, rotation sensation, eyeball rotation, discomfort in all experiments.
Fecci R. et al, 1971	65-80 dB; 8 Hz; Industrial exposure within 4 months	Arterial pressure indices were very stable within 4 months. Only 18% had mild AP decrease and 22% had mild AP increase. Pulse rate was stable. ECG changes were not found.
Malyshev E.N., Skorodumov G.E., 1974	135 dB; 10 Hz; 15 min	Cardiovascular status examination has revealed pulse rate increase (5-30 min^{-1}), minimal AP increase (20 mm) and maximal AP increase (15 mm) in males.
Pimonow L., 1976	-	10 year material generalization has suggested to the infrasound pressure limit of 140 dB for space fliers and 120 dB for space flight technical personnel.
Johnson D., 1974	144 dB and more; 1 – 30 Hz	160 dB is considered to be maximum permissible even for short-time exposure.

Note: * SPL – sound pressure level, dB

The infrasound induces tympanic hyperthermia, which can be observed both at the time of exposure and thereafter (Nixon C., Johnson D., 1973). This hyperthermia can vary from mild to severe grade; the severe hyperthermia can be in the whole hammer handle. Detailed infrasound influence consideration for 100-140 dB was elaborated for aural analyzer taking into account effects of harmonics generated in case if intensive infrasound exposure. Some examined individuals have not been found aural changes whereas others have been detected to develop temporary shift of aural sensitivity threshold. The aural analyzer sensitivity to the infrasound exposure is generally similar to that for higher frequency noise, if the temporal aural threshold shift (TATS) is considered. The infrasound TATS variability is similar to that for sound frequencies.

In case of infrasound levels above 172 dB, D. Johnson (1974) has observed tympanic perforation and middle ear muscle hyperemia in animals, however, the animals have not manifested anxiety. The author indicates that he has exposed himself to this infrasound for 30 seconds and found that painful sensations are absent but tympanic mechanical massage sensation is present. In case of the whole body exposure to 144 dB infrasound, the exposed persons were found to have voice modulation; the increase of middle ear pressure was noted for > 132 dB.

The peculiarity of industrial infrasound exposure consists in the "pure" infrasound absence; usually it is combined to low frequency aural noises. V.I. Palgov and N.N. Doroshenko (1975) have examined aural abilities in compressor operators exposed to infrasound (113 dB) combined to stable noise (85 dB). The comparison group was composed of mechanical workshop workers exposed to <90 dB without recorded infrasound exposure. It was established that the percentage of people with occupational bradyacuasia (grades III-IV) is 11.2% against 2.5% in mechanical workers. The aural function peculiarity of combined infrasound and noise exposure of compressor operators was the increase of aural thresholds at low and high frequencies, which certifies to the involvement of both basal and apical parts of the cochlea.

The industrial infrasound study has not revealed specific effects (Mozhukhina N.A., 1979). However, the examination of the functional state of compressor operators within work day dynamics has revealed the aural threshold increase at 125, 250, 500, 2000, and 3000 Hz, for < 5 dB in average. Besides, some decrease of hand persistence, diastolic arterial pressure increase, and ECG R-R interval decrease was found. When comparing stability diagrams, the moderate (< 40%) increase of the shift area of the gravity center projection was noted which indicates to the equilibrium system change. It was judged that industrial infrasound combined to wide band noise has not more significantly affected in aural analyzer and cardiovascular system, if compared to that of the wide band noise only.

The infrasound exposure is accompanied by the cerebral hemodynamics depression expressed by the venous outflow complication in skull cavity, which phenomenon has occurred at ~ minutes 7-10 of the infrasound exposure (Karpova N.I. et al, 1979). 135 dB infrasound at 10 Hz has evoked larger increase of rheography wave amplitude, its anacrotic phase extension and the tonic tension index decrease, if compared to that at 5 Hz.

When considering the issue of the harmful infrasound effect in aural analyzer, the harmful vestibular effect has to be considered. Studies elaborated by N.S. Yowart (1974) have to be discussed in this context. When doing monoaural infrasound stimulation, the expressed vertical nystagmus was noted in 85% of cases. The sound pressure level applied was in the range of 130 dB to 146 dB and frequency range was 2 Hz to 10 Hz. These data have given the opportunity to suggest that infrasound affects vestibular apparatus; the most effective frequency was found to be ~ 7 Hz, which corresponds the sensitivity range of vestibular channels. The vertical nystagmus induced by infrasound indicates to the effect in otolith system.

The infrasound oscillations affect the supreme nervous activity. Experiments to compare infrasound versus alcohol were tried (Kyriakides K., Leventhall H.G., 1977). These studies have demonstrated that 2 Hz to 15 Hz infrasound of 110-120 dB levels has negatively affected the ability to fulfill simple tests; the equilibrium support, reaction time and surveillance function were also worsen. The workability analysis has demonstrated that both infrasound and alcohol has induced 10% worsening of basic task execution ability.

Experimental studies (Reutov O.N., 1978) devoted to infrasound (5 Hz and 10 Hz, 135 dB to 100 dB, 15 minutes exposure) have revealed that largest percentage of complains was composed of subjective sensations of general fatigue, weakness, depression, disseminated attention, sleepiness, heavy head, and ear pressure (in 100% of cases). Large number of complainers has indicated to breath obstruction, chest and abdominal wall vibration. The decrease of the breath rate, cardiac outflow amplitude decrease, perception speed decrease, increase of latent period of visual-motor reaction (for 14-8% in case of 135 dB and for 5-6% in case of 100 dB) were objectively noted.

The respiratory function and cardiovascular system are soundly affected by the infrasound. Animal experiments (dogs, monkeys) have demonstrated that 166 dB infrasound exposure

has significantly decreased the breath rate and the breath was stopped in case of 172 dB infrasound exposure. The total exposure time was 14 hours (Johnson D., 1974). In case of 190 dB infrasound exposure within 7-20 minutes the expansion of blood vessels width and lung hemorrhages were found (macroscopic and microscopic examinations), which has concluded to serious infrasound effects in the blood vessels in case of 180 dB level. Studies tried in 42 young males exposed to 7.5 Hz and 130 dB (50 min) have indicated the increase of minimal arterial pressure, whereas the maximal arterial pressure has not changed.

E.N. Malyshev and F.E. Skorodumov (1974), P. Borredon and J. Nathie (1974) have shown that 15 minutes infrasound exposure results to abnormal state of cardiovascular system. The pulse rate was increased for 5-30 min^{-1} depending upon the infrasound intensity; minimal arterial pressure was risen for 20 mm, maximal arterial pressure was risen for 15 mm, muscular tonus was decrease for 3-12%, and breath rate was increased for 4 min^{-1} and more.

The exposure to large infrasound levels was noted by the chest and abdominal wall oscillations and so-called thoracic abdominal effect (Sanova A.G., 1977; Karpova N.I. et al, 1979). Such phenomena can be explained by the presence of acoustic impedance of these body parts (i.e. they are good infrasound conductors), so the major portion of the infrasound energy penetrates throughout the chest and abdominal wall.

The resonance frequency of the whole system of "abdominal cavity – chest" is in the range of 40-60 Hz in case of the volumetric infrasound exposure; at the same time, the chest resonance in case of single dimensional oscillations (human vibration experiment) is 4-8 Hz (von Gierke H.E., 1974). To get the objective examination of the infrasound health effects, H.E. von Gierke has made the model of human body to imitate acoustic impedance and to assess infrasound exposure intensity assessment to get the lung damage similar to that from the shock waves. These studies have demonstrated that belts application is inconvenient to suppress abdominal oscillations, because of more dangerous resonance oscillations at higher frequencies (10 Hz). It was concluded that high intensity infrasound is less harmful than correspondent levels of higher frequency sound or vibration.

The survey (Broner N., 1978) devoted to low frequency noise effects in human has considered infrasound (0-20 Hz) and low frequency noise (20-100 Hz) effects; it was noted that low frequency noise effect is more expressed than the infrasound one, though both effects are poorly investigated.

R.D. Gabovich et al (1979) have examined chronic infrasound of 8 Hz and 90, 115 and 135 dB intensities in case of animal exposure within 4 months (2 hours per day). This study has demonstrated that infrasound affects energy metabolism and body ultrastructure of rat myocardium. Changes of different intracellular structures (mitochondrias, endoplasmic reticulum, Holdgi apparatus) were already observed at 90 dB infrasound exposure. The resulting disturbance of routine enzymatic activities was found. In case of the exposure to 115-135 dB, the disturbances of the oxidative phosphoring processes, corticosterone increase in plasma, and catecholamine content decrease were noted, which is related to the long term stimulation of sympathetic adrenal system. Similar studies as well as studies elaborated by S.V. Alexeev and E.N. Kadyskina (1976), V.I. Vasiliev (1976), N.I. Karpova et al (1976), V.L. Ponomareva et al (1979) including some indices of albumin metabolism and microcirculation of soft cerebral cover vessels in white rats has given the opportunity to clarify intimate mechanisms of health effects induced by the infrasound exposure.

Thus, though the comprehensive investigation of LFAO health effects is still to be continued, it can be concluded that infrasound affects functional state of aural and vestibular analyzers, respiratory function, nervous and cardiovascular systems, which effects depend upon pressure level and frequency of the infrasound. The peculiar attention should be

attracted to nervous emotional system, workability and fatigue ability, when investigating infrasound effects in human for hygienic purposes.

Many researchers have described different infrasound reactions of cochlear vestibular apparatus. Recent volunteer studies (Kuralesin N.A., 1997) devoted to peculiarities of cochlear vestibular apparatus reaction has demonstrated the presence of alternative frequency-effect ratio of aural and vestibular sensitivity. The increase rate of vestibular related reactions was 2-2.8 times higher than that for aural ones. The sum of these two mechanisms was considered to be responsible for resultant spectrum of functional and pathological changes.

Basing upon data of N.F. Izmerov et al (1998), the vestibular analyzer receptors are considered to be adequate to the infrasound perception rather than aural ones. The specific peculiarity of nuclei vestibular complex is the unusually large development of outer ways connecting nuclei to different anatomical structures of the brain, especially to dorsal vagus nuclei. These connections provide global influence of the vestibular apparatus in all functions including whole cross-striated musculature and vegetative nervous system (VNS). Effect reactions induced by the infrasound stimulation of the labyrinth are similar to the symptom complex induced in case of motion disease; apparently, it can be attributed to the infrasound motion disease. Taking into account the tight relationship of vestibular analyzer with VNS centers and dorsal vagus nucleus, one can suppose that the vegetative disturbance development is basically determined by the vestibular-vegetative interaction activation (Izmerov N.F., Suvorov G.A. et al, 1998).

Basing upon original studies and literature references, the Research Institute of Labor Medicine has developed the concept of pathological pattern for the infrasound exposure of the human organism. This pattern is very comprehensive, however some basic statements can be emphasized. The peculiar feature of the infrasound damage is the development of combined inter-related pathological processes. One of such processes is pre-caused by regularities of general adaptation syndrome and the other one is pre-caused by the alteration of the cerebral nervous formations, endocrine target organs and internal organs. The major pathogenetical part of this process is the development of tissue hypoxia resulted from cerebral hypertension caused by liquor hemodynamic and microcirculatory disturbances. The universal consequence of hypoxia is the membrane disorganization resulting to the enzyme leakage from sub-cellular structures and cells into the tissue liquid and blood; this is the main point of secondary hypoxia alteration of the tissue (N.F. Izmerov et al, 1997).

Basic objective and subjective signs of the infrasound exposure and its harm and health risks classification is provided by Table 3

Table 3 – Risk ranges of infrasound exposure (Izmerov N.F. et al, 1997)

Risk range	Frequency, sound pressure level, exposure time	Effects
1	2	3
1 fatal levels range	180 - 190 dB	Fatal effect (lung alveoli rupture).

1	2	3
2 extreme effect range	0 – 20 Hz < 140 – 150 dB 90 s	Middle ear pressure sensation.
	50 – 100 Hz > 154 dB 2 min	Headache, strangulation, caught, fogginess vision, fatigue, strong chest pressure sensation, salivation, swallowing pain. Tolerable limit symptoms.
	100 Hz 153 dB 2 min	Nausea, giddiness, discomfort, skin redness.
	60 Hz 157 dB 2 min	Caught, strong chest pressure sensation.
	73 Hz 150 dB 2 min	Strangulation, salivation, swallowing pain, giddiness.
	0 – 50 Hz < 145 dB 2 min	Chest vibration sensation, mouth dryness, breath rhythm change, general fatigue, unreal false feeling. Below voluntary tolerance limit.
3 high health risk range even for periodic exposures	1 - 20 Hz 140 - 145 dB	Chest and abdominal cavity percussion is resulted by jet engine operation, the state of sea sickness is occurred, and vestibular disturbances are developed including static kinetic disorders, giddiness, and nausea. In case of long term exposure the development of asthenia, general fatigue, mental workability decrease, irritability, sleep disorders were found; in some cases mental disorders are occurred due to anxiety and fear.
3-A high health risk range for relatively long-term exposure	2, 4, 8, 16 Hz 134, 129, 126, 123 dB 15 min	Subjective sensorial somatic vegetative discomfort: nausea, giddiness, pressure and massage of tympanic membranes, fever-like tremor, movements in the area of stomach and intestine, chest pain, visceral pain, headache, eye pain, anxiety, salivation, transient stiffness of palate and facial skin of apparent sensorial cortical genesis, voice modulation of limbic genesis. These signs indicate to the syndrome of infrasound (hypothalamic diencephalic) crisis. Objective reactions: middle ear mucosa hyperemia, static kinetic stability decrease, vestibular vegetative reactions (systolic arterial pressure decrease, pulse rate decrease etc); expressed decrease of CNS activation according to the coefficient of inter-hemispheric asymmetry. Increased reactions of aural analyzer in case of infrasound frequency increase and increased sensorial and CNS reactions with frequency decrease.
	10 Hz 135 dB 15 min	Expressed sensorial somatic vegetative discomfort: headache, giddiness, tympanic pressure, internal organ oscillation sensation, mouth dryness, breath obstruction.

1	2	3
4 moderately elevating health risk range	110 -120 dB	Several minutes exposure is not health harmful. Longer exposure can induce follow-up effects in vestibular and aural analyzer and other body systems.
	2, 4, 8, 16 Hz 115 dB 1 and 5 hours	Interfering, irritating effects, moderate discomfort: sleepiness, headache, ear "jamming", body vibration sensation. Complains are increased with the frequency decrease. Unfavorable effects in many physiological indices. Confident correlation to subjective perception expressiveness and vegetative, stabilometric and other indices of functional state of the organism.
5 significant risk of chronic health disorders, especially if combined to other factors	100 - 110 dB 16, 105, 1 h	Complains to interfering, irritating effects, giddiness, nausea, irritability, sleepiness, ear whistling, headache. Objective signs of decreased attention, static kinetic stability, pulse rate decrease, CNS functional activity decrease (inter-hemispheric asymmetry coefficient data).
	8, 16 Hz 100 dB 1 hour	Complains to throat scratching, cough, noise and pain in ears, fatigue, sleepiness, absent-mindedness. Physiological reactions are unchanged.
	8, 16 Hz 90 - 100 dB	Short time exposure is not health harmful; daily exposure results to complains and discomfort. Significant increase of spontaneous abortions rate (from 11% to 17%) and pregnancy complication rate (8 - 22%) in young female workers exposed to combined low intensive factors: 75 dBA noise and 8 Hz infrasound of 90 dB.
6 unclear and hard detectable health risk range	8 - 16 Hz < 90 dB	Isolated short/long time exposure is not heath harmful. Combination with noise and vibration as well as with nervous emotional tension can significantly amplify negative infrasound effects.
7 ecologically unfavorable population effect range for populated areas	16 Hz 109 dB	Significance of the population exposure was confirmed by the difference of complain rates (disturbances of day and night rest, poor sleep, frequent headaches). Infrasound causes interfering and irritating effects and induces functional disturbances.

Note: SAP – systolic arterial pressure, PR – pulse rate, CFJI – "critical frequency of joint images" test. > 150 dB are completely intolerable for examinees.

Hygienic regulation of low frequency acoustic oscillations

First Russian regulation of the industrial infrasound was adopted by the State Standard (GOST) No. 12.1.003-76: "Noise. General safety requirements". Despite the industrial noise was only considered by this standard, item 3.2 of this document indicates that "... even short-time stay in the areas of active sound pressure levels above 135 dB of any octaval band is forbidden."

After the adoption of this standard, basing upon the analysis of the literature data, experimental and physiological hygienic studies, the hygienic regulation of low frequency and infrasound bands of acoustic oscillations of the air media was elaborated. It is convenient to consider the progress of the infrasound hygienic regulation versus the accumulation of new knowledge on the health effects of the low frequency acoustic oscillations.

First national hygienic infrasound standards were developed by the Institute of Biophysics in 1979. These standards were adopted at inter-agency level due to the initiation of studies of health effects of low frequency acoustic oscillations and based upon original experimental data and physiological hygienic examinations of volunteers obtained within first 3 years of work (Table 4).

Table 4 – Occupational safety standards of infrasound (Institute of Biophysics, 1979)

Octaval frequency bands, Hz	0.88 - 1.4	1.4 - 2.8	2.8 - 5.6	5.6 - 11.2	11.2 - 22.4	22.4 - 45.0
Averaged geometric frequencies of octaval bands, Hz	1	2	4	8	16	31.5
Permissible levels of sound pressure, dB*	108	106	104	102	100	98

*Note: if total exposure time is less than 6 hours/working day, permissible levels will be increased according to the duration:
1-3 hours – for 6 dB;
1/4 h to 1 h – for 12 dB;
5 – 15 min – for 18 dB;
<5 min – for 24 dB.
Even short-time exposure to > 140 dB is prohibited.

First official state infrasound standards were elaborated by Research Institute of Labor Hygiene and Occupational Diseases of the USSR Academy of Medical Sciences (at present, Research Institute of Labor Medicine of Russian Academy of Medical Sciences), which standards were entitled: "*Hygienic standards of the infrasound at workplaces», No. 2274-80.* (Adopted in 1980; out of force at present).

These standards are applicable not only to the occupational exposure. The standardized infrasound indices are sound pressure levels in octaval bands of averaged geometric means of 2, 4, 6, 8, 16 Hz calculated according to the following formula (dB):

$$L = 20 \lg P/P_0 ,$$

where $P_0 = 2 \cdot 10^{-5}$ Pa.

For variable infrasound the standardized feature is the general level of the sound pressure on "linear" scale, dB "Lin".

It is acceptable to evaluate sound pressure levels in third-octaval frequency bands of 1.6, 2, 2.5, 3.15, 4, 5, 6.3, 8, 10, 12.5, 16, 20 Hz. These levels should be re-calculated to levels of octaval bands of averaged geometric frequencies given by "Methodological indications on measurements and hygienic assessment of noises at workplaces" No. 1844-78, Ministry of Health of the USSR (Table 5).

Table 5 – Sound pressure levels (dB) in octaval bands

Sound pressure levels (dB) in octaval bands at average geometric frequencies (Hz)					General sound pressure level (dB) "Lin"
2	4	8	16	31.5	
105	105	105	105	102	110 dB

Note: 31.5 Hz octave was included, because it was not regulated by the State Standard, GOST 12.1.0003-76 entitled "Noise. General Safety Requirements"

In 1989 the documents on *"Sanitary standards of permissible levels of infrasound and low frequency noise in the living areas", SanPiN 4948-89* and *"Methodological indications to sanitary epidemiological surveillance services for management of the implementation of "Sanitary standards of permissible levels of infrasound and low frequency noise in the living areas", SanPiN 4948-89", No. 4949-89.* (Approved in 1989; out of force at present time).

These sanitary standards have established maximal permissible levels of the sound pressure for populated areas (i.e. were applicable in the general public).

The standardized parameters of continuous infrasound and low frequency noise are sound pressure levels, *L,* dB, at octaval bands of averaged geometric frequencies of 2, 4, 8, 16, 31.5 Hz or at 1/3 octaval bands of averaged geometric frequencies of 1.6, 2, 2.5, 3.15, 4, 5, 6.3, 8, 10, 12.5, 16, 20, 25, 31.5, 40 Hz.

Standardized parameters of intermittent infrasound and low frequency noise are energy equivalent sound pressure levels, *L,* dB, at octaval or at 1/3 octaval bands of averaged geometric frequencies listed above.

Permissible levels of the infrasound and low frequency noise pressure, dB, in the living area are given by Table 6.

Table 6 – Permissible infrasound pressure levels, dB

Frequency, Hz	2	4	8	16	31,5
Sound pressure, dB	90	90	90	90	90

Note: third octaval sound pressure levels are 85 dB.

To get the approximate assessment of the infrasound level, one can apply general sound pressure level on the "linear" scale and difference between readings of "linear" and "A" scales of the noise meters of classes 0 and 1. The permissible value of the general sound pressure level on the "linear > 2 Hz" scale is 90 dB. The grade of the infrasound expressiveness was determined by the difference of $L_{\text{“lin”}} - L_{\text{“A”}}$: 6-10 dB (infrasound presence sign), 11-20 dB (moderate expressiveness), 21-30 dB (expressed infrasound), and > 30 dB (significant expressiveness).

In 1997, basing upon elaborated studies and new data on infrasound effects described by the present monograph, researchers of Labor Medicine Institute, Erisman Institute, St.-Petersburg Medical Academy, and Voronezh State Medical Academy named after N.N. Burdenko have elaborated sanitary rules and standards for the infrasound exposure.

Proposed limit levels for octaval bands of 2, 4, 8 and 16 Hz were based upon the whole variety of unfavorable health changes and entitled *"Infrasound at workplaces, living and public premises and populated areas", SN 2.2.4/ 2.1.8.583-96.*

This regulative document is in effect at present time and establishes criteria of safety and harmlessness for human environment as well as the requirements for favorable conditions f human activities.

The present sanitary rules provide classification, hygienic regulations and requirements of measurement and assessment of the infrasound at workplaces, living areas and premises as well as requirements for the protection measures and prophylaxis of unfavorable effects and monitoring (Table 7).

Table 7 – Permissible infrasound levels at workplaces, living and public premises and populated areas

No.	Premise	Sound pressure levels, dB, in octaval bands of averaged geometric frequencies, Hz				General sound pressure level dB "Lin"
		2	4	8	16	
1.	Different jobs inside industrial premises and production areas:					
	- Different physical intensity jobs	100	95	90	85	100
	- Different intellectual emotional tension jobs	95	90	85	80	95
2.	Populated area	90	85	80	75	90
3.	Living and public premises	75	70	65	60	75

Hygienic requirements are applicable to all new created, modernized, imported and operated machines and equipment as well as to processes specific to infrasound generation; they are presumed for usage of specialists when designing, expertizing technical documentation (Standards, Technical Terms, etc.), evaluation, certifying and distributing production in the population.

The analysis of comprehensive hygienic, physiological, biochemical and morphological studies also indicates to the necessity to introduce frequency correction with the decrease of 5-6 dB/octave, alternatively to values adopted by the international standard, ISO 7196 (12 and 24 dB) which are based upon the aural effects and subjective assessment of the infrasound irritating effect.

Thus, new data on the infrasound effect mechanism have given the opportunity to propose the new principle of the safe level regulation. The proposed limit levels for octaval bands of 2, 4, 8 and 16 Hz are based upon the whole variety of unfavorable effects of the whole organism. It is suggested that the exposure to such infrasound levels within the whole working shift and occupational term (up to 40 years) would not induce specific and non-specific diseases. Basing upon physics, acoustics and physiology peculiarities of the factor and medical prophylaxis requirements, hygienic principles of the unfavorable factor exposure limitation were also developed (Table 8).

Table 8 – Hygienic regulation principles of infrasound unfavorable exposure (Izmerov N.F. et al, 1999)

Factor peculiarities	Medical technical requirements and prophylaxis directions
1. Physics peculiarities (large wavelength and low attenuation with distance), which determines ineffectiveness of traditional protection methods applying: - distance (large distance required); - mass (poor sound isolation); - shielding (unreal sizes of shields); - time (applicable for low intensities only); - individual protection mans (low efficiency, ± 5 dB with resonance).	1. Constructive and design-acoustic solutions: - acoustics calculations of highways, tunnels, bridges etc.; - traffic flow management; - geometric principles for vulnerable territory shielding (kindergartens, schools, hospitals etc.).
2. Acoustics and physiology peculiarities: - large importance of each decibel because of narrow range of reacting from perception to the pain threshold; - specificity of aural and extra-aural effects.	2. Technological processes and equipment: - optimization of geometric and kinematics parameters; - dynamic anti-phase attenuators with resonance absorption; intensimetry techniques for diagnosis and correction of acoustic fields.
3. Peculiarities 1 + 2 in case of the MPL excess strongly increase the hygienic significance of the problem	3. Peculiarities of medical assistance of operators, car drivers etc. (occupational selection, preliminary examination, modes of work and rest etc.)

The obtained results were the justification of infrasound ranking versus its parameters and according to health risk ranges for workers and population, which was the significant input to Manual (R.2.2.013-94) on Hygienic criteria of labor condition assessment according to harm indices and danger of industrial factors, difficulty and intensity of work process.

The time dynamics of permissible levels of infrasound and low frequency acoustic oscillations (1973-2000) is summarized by Table 9 and Figure 1.

Table 9 – MPLs dynamics for LFAO and infrasound in 1973-2000

1973	**MPLs recommended by Paris International colloquium (CNRS)**				
Frequency, Hz	1	2	4	8	16
Sound pressure levels, dB	135	130	125	120	116
1973	**MPLs recommended by D. Johnson**				
Frequency, Hz	1	2	4	8	16
Sound pressure levels, dB	139.6	135	130	125	120
1974	**MPLs which excess can damage the hearing (C.W. Nixon)**				
Exposure duration	Frequency, Hz				
	1	5	10	20	

8 minutes	150	150	145	140
1 hour	145	138	135	132
8 hours	136	129	126	123
24 hours	131	124	121	118

1975	**Short-time (< 8 minutes) exposure MPLs (von H.E. Gierke et al)**		
Frequency, Hz	1 – 7	8 – 11	12 – 20
Sound pressure levels, dB	150	145	140

1979	**Occupational exposure MPLs (Institute of Biophysics)**					
Exposure duration	Average geometric frequencies of octaval bands, Hz					
	1	2	4	8	16	31.5
6 hours	108	106	104	102	100	98
From 1 hour to 3 hours	114	112	110	108	106	104
From 15 minutes to 1 hour	120	118	116	114	112	110
From 5 to 15 minutes	126	124	122	120	118	116
Less than 5 minutes	132	130	128	126	124	122
Note: Even short-time exposure to sound pressure level of more than 140 dB is prohibited						

1980	**"Hygienic standards of infrasound at workplaces", No. 2274-80 (Research Institute of Labor Hygiene and Occupational diseases of the USSR Academy of Medical Sciences et al)**					
Average geometric frequencies, Hz	2	4	8	16	31.5	Integral SPL, dB "Lin"
Sound pressure levels, dB	105	105	105	105	102	110

1981	**MPLs for low frequency and infrasound noise at workplaces (N.I. Karpova, E.N. Malyshev)**							
Average geometric frequencies, Hz	0.5	1	2	4	8	16	31.5	63
Sound pressure levels, dB	120	117	114	111	108	105	102	99

1989	**"Sanitary standards of infrasound and low frequency noise at populated areas" SanPiN 4948-89 (Research Institute of Labor Hygiene and Occupational diseases of the USSR Academy of Medical Sciences et al)**				
Average geometric frequencies, Hz	2	4	8	16	31.5
Maximum permissible sound pressure levels, dB	90	90	90	90	90

1996	**Infrasound at workplaces, living and public premises and populated areas" (Labor Medicine Research Institute of Russian Academy of medical Sciences et al)**				
Type of premises	SPL, dB, in octaval bands with average geometric frequencies, Hz				Integral SPL, dB, "Lin"
	2	4	8	16	
Jobs of different intensity inside industrial premises and at the industrial territory:					
- different intensity jobs	100	95	90	85	100
- intellectual and emotional jobs	95	90	85	80	95
Populated areas	90	85	80	75	90
Living and public premises	75	70	65	60	75

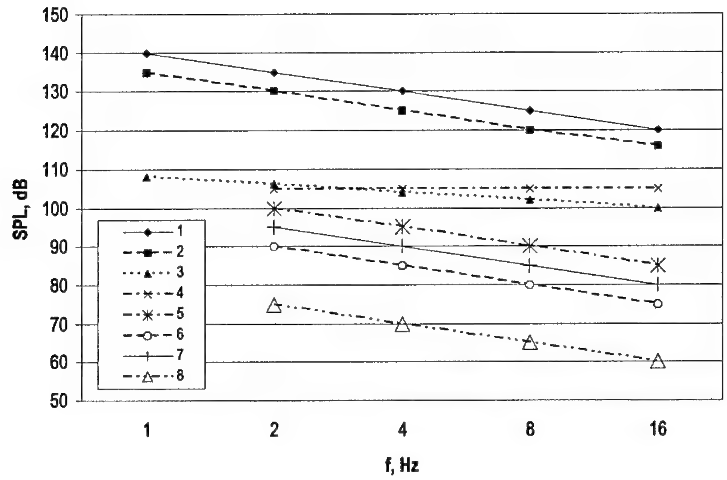

Figure 1 – MPLs dynamics for LFAO and infrasound in 1973-2000

1 - MPLs recommended by D. Johnson and C. Nixon (1973);
2 - MPLs recommended by Paris International colloquium (CNRS) (1973);
3 - MPLs recommended by Institute of Biophysics (1979);
4 – MPLs recommended by Research Institute of Labor Hygiene and Occupational diseases of the USSR Academy of Medical Sciences et al (1980);
5, 6, 7 and 8 – modern MPLs recommended by Labor Medicine Research Institute of Russian Academy of medical Sciences et al (1996); jobs of different intensity inside industrial premises and at the industrial territory (5), intellectual and emotional jobs (6), populated areas (7), living and public premises (8).

Acoustic parameter measurement

Depending upon the complexity of noise investigated and investigation purposes, the acoustic measurement practice applies portable devices (noise meters) or the equipment complex composed of measurement tract, magnetic recorder and analyzer.

Noise meters are subdivided into four accuracy classes as follows: reference measurement devices (class 0); accurate laboratory and field measurement devices (class 1); routine accuracy measurement devices (class 2); approximate measurement devices (class 3). The routine accuracy presumes measurement error below ±1 dB, with 68% confidence interval. Frequency range is determined by the microphone and should be 20 Hz–12.5 kHz (class 1), 20 Hz-8 kHz (class 2), 31.5 Hz-8 kHz (class 3).

Noise meter contains frequency correction circuits for scales "A", "B", "C", "D" and "Lin"; averaging modes correspond to time characteristics of "Fast", "Slow", "Impulse", and "Peak" and give the opportunity to measure sound level (dB"A") and sound pressure level (dB). "Fast" and "Slow" averaging modes are used to measure stationary noise processes and "Impulse" mode is used for non-stationary processes containing pulses. If the "Slow" mode measurement demonstrates the sound pressure level change for less than 5 dB, such noise is named as continuous; otherwise it is intermittent.

To measure equivalent sound level integrating noise meters are available. Accuracy classes of integrating noise meters are that for routine noise meters. The noise dose is measured by dosimeter, which is the integrating noise meter.

The noise measurement complex is usually composed of microphone, preamplifier, microphone power supply, recorder, frequency analyzer, paper recorder and reference

sound source. Recently, the computer based modules are used for recording and processing of acoustic measurement results.

The list of commercially available equipment is rather long. At the period of Mutual Economy Aid Council (SEV) manufacturers of noise measurement equipment were Robotron-Messelektronik (East Germany) and Vibropribor (USSR, Taganrog). Other firms include Metravib (France), Ono Sokki (Japan), Endevco (USA), Bruel and Kjaer (Denmark). This list can be prolonged because worldwide noise measurement equipment needs are very high and each developed country has its own manufacturer.

The most comprehensive assortment of acoustic equipment is manufactured by Bruel and Kjaer (Denmark), which company elaborates original research to develop new techniques and measurement equipment together with their quality assurance according to international practice. The survey of this company equipment would provide most complete and modern view of acoustic measurement equipment.

Conclusions

1. 1976-2002 comprehensive studies of hygienic, clinical physiological, and experimental character give the opportunity to conclude that low frequency acoustic oscillations are the harmful environmental factor affecting health and workability of human. Therefore, the actuality of the hygienic issue of the infrasound is present and requires future hygienic, medical biological, and pathogenetic research of this poorly known physical factor of the environment.

2. Subjective reactions (especially those described in publications issued in early 1970^{th}) to the low frequency acoustic oscillation exposure (giddiness, nausea, general fatigue, unjustified fear, spatial disorientation, intestinal spasm, fever-like tremor etc) are the clear overestimation. Basic subjective symptoms in case of high pressure levels of infrasound and low frequency acoustic oscillations (up to 155-160 dB) and short exposure time (5-10 minutes) are voice modulation, feeling of chest prelum coinciding to frequency of variable pressure and correspondent breath obstacle or breath rhythm change. Other subjective reactions described in literature seem to be more dependent from psychological state of the complainer rather than to low frequency oscillation themselves..

3. The "non-aural" infrasound has never been contacted by author; it relates to both natural and artificially generated one. Therefore, the attitude of the majority of researchers regarding the absence of "pure" infrasound (i.e. the infrasound non-accompanied by aural sounds, especially of high aural frequencies) in the natural environment seems to be completely valid.

4. The "resonance theory" of the infrasound effects and correspondent "harmful" biological rhythms (like, pulse rate, EEG rhythms or "resonance frequencies of internal organs") are more para-scientific ones; the scientific knowledge of infrasound effects does not involve such issues.

5. Considerations of the specificity of low frequency acoustic effects regarding the possibility for the influence in processing and transfer of the information inside the organism) so-called "information" infrasound effects) were not experimentally confirmed within recent 25 years.

6. The experimental studies of biological effects of LFAO clearly indicate to the necessity to consider two magnitudes (sound pressure and oscillation velocity vector), when examining this exposure and despite dosimetric complications. The assessment only based upon the sound pressure level seems to be erroneous.

7. Until now, pathogenetic mechanism of LFAO reactions of experimental animals and human is not completely clear. The proposed mechanism of diencephalic crisis (Izmerov N.F. et al, (1998), seems to be overestimation of the possible effect grade.

8. At present time, the only fact of significant liquor-hemodynamic and microcirculatory disturbances in lungs, brain and heart is firmly established; in their turn, these disturbances result to hypoxia and followed pathological changes of these organs. The hypoxia has to be considered as the important pathognomonic consequence of the LFAO exposure. Microcirculatory disturbances are manifested according to the exposure intensity; all kinds of laboratory animals (mice, rats, rabbits, dogs, monkeys, sheep) have got fine spot hemorrhages, blood stasis, erythrocyte aggregation, sludge phenomenon.

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Technological Environment Oscillations of Low Frequency (below 20 Hz) as a Risk Factor for Human Health: Hygienic, Medical, Biological, and Pathogenic Mechanisms

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Preface

The present monograph has been prepared under ISTC Project No. 2361p on Technological low frequency (below 20 Hz) oscillations in the environment as the human health risk factor: medical, biological and pathogenetic mechanisms, according to trilateral Partnership Agreement between International Science and Technology Center (ISTC, Moscow), European Office of Aerospace Research and Development (EOARD, London, UK), and State Research center - Institute of Biophysics (SRCIBP, Moscow, Russia).

The monograph considers and analyzes data of Russian and foreign researchers for the period of 1970-2002, which data are devoted to the one of fundamental hygienic issue arisen from science and technology progress, namely the health effects of man-made low frequency acoustic oscillations.

The major emphasis of the monograph includes Russian research done within recent thirty years. The monograph provides detailed descriptions of research studies in Russia, which studies have provided the basis of national hygienic regulation of low frequency acoustic oscillations.

Leading research institutions involved in the field include Labor Hygiene Faculty of Leningrad Sanitary Hygiene Medical Institute (now St.-Petersburg State Medical Academy named after I.I. Mechnikov), Research Institute of Labor Medicine of Russian Academy of Medical Sciences, Normal Physiology Faculty of Military Medical Academy named after S.M. Kirov (St.-Petersburg), Hygiene Faculty of Voronezh State Medical Academy named after N.N. Burdenko, St.-Petersburg Institute of Railroad Engineering, Moscow Hygiene Research Institute named after F.F. Erisman and others.

The monograph is particularly addressed to previously unpublished studies on health effects of low frequency oscillations, which studies have been elaborated since 1976 in State Research Center - Institute of Biophysics of the Federal Agency on Medical Biological and Extreme Problems at the Ministry of Health of Russian Federation (SRCIBP). These studies were done in collaboration with a number of co-authors including technical research organizations of Russia, where the necessary technical basis was developed. Studies at especially created installations were done in small and large laboratory animals. Clinical physiological studies were done in volunteers.

The first chapter of the monograph provides general physical concepts related to low frequency oscillation acoustics as well as to peculiarities of their generation and propagation in the environment.

Second chapter provides history and general principles of research technical basis development together with the brief

description of some installations devoted to medical biological studies both in chamber conditions and in case of the free propagation of low frequency acoustic oscillations (formed acoustic wave and long distance area). All installations described were applied in the Institute of Biophysics since 1976.

Third chapter is devoted to the literature survey of Russian and foreign studies devoted to health effects of man-made low frequency acoustic oscillations for more than 25 years of the research. This chapter provides detailed description of basic proceedings and study results of Russian scientists (taking into account English speaking reader interests). These publications include one of the first in the field monograph written by N. Karpova and E. Malyshev on Low frequency acoustic oscillations in industry (1981). The fundamental monograph written by N. Izmerov, G. Suvorova, N. Kuralesin, and V. Ovakimov on Infrasound as human health risk factor (1998) is surveyed; this publication justifies the factor ranking versus its parameters and human health risk zones, provides the infrasound regulation concept based upon comprehensive hygienic, clinical physiological, medical biological and pathogenetic criteria, and formulates the understanding of the infrasound hypothalamic syndrome (diencephalic crisis) development induced by this factor.

The special attention should be attracted to the monograph written by V. Samoylov, G. Ponomarenko, and L. Enin on Low frequency bioacoustics (1994), where regulations of the low frequency bioacoustics are formulated and justified, biophysical basics of biological system reacting to low frequency acoustic oscillations (LFAO) are described, and existing viewpoints on physiological mechanisms of the forming of these reactions are generalized.

Finally, the recently published monograph (Akhmetzyanov I.M., Grebenkov S.V., and Lomov O.P., St.-Petersburg Military Medical Academy) entitled "Noise and infrasound. Hygienic aspects" (2002) has analyzed modern issues of noise and infrasound as of industrial and environmental factors resulting to elevated negative exposure in human.

Some most important papers and monograph sections of Russian authors are quoted as a whole and small font printed in this chapter.

This chapter has also systematized and generalized experimental studies as well as medical biological aspects of the infrasound exposure in human together with results of clinical physiological and physiological hygienic tests in volunteers. Some simulation experiment results are given including the combined exposure to low frequency acoustic oscillations and other non-ionizing factors like electromagnetic radiation etc.

The fourth chapter is completely devoted to infrasound hygienic regulation issues as well as to the possible pathogenetic mechanism

of the exposure in human body. The chronological sequence is provided for all regulating documents and standards on maximum permissible levels of the infrasound exposure adopted in Russia in 1978-2002.

The fifth chapter contains generalized data of clinical monitoring of persons employed with investigated factor and volunteers participated in studies on LFAO health effects. These regular medical examinations were done at the clinical department of the Institute of Biophysics within the whole period of such occupation.

The monograph is finalized by author conclusions summarizing more than 25 years of the original research of simple harmonic low frequency acoustic oscillations in the environment.

The monograph contains the complete list of references to Russian and foreign publications (for the period of 1970-2002, approximately), which enlists more than 450 references devoted to medical biological aspects of the human and animal exposure to man-made low frequency acoustic oscillations. All references are given in original language and Russian references are translated into English. The same is for author index.

One of the annexes of the monograph include the detailed abstract containing basic statements on biological effects and hygienic regulation of low frequency acoustic oscillations (according to the Partnership Agreement terms).

Besides, this annex contains publication devoted to discussible issues of the research of biological effects of the infrasound, particularly, to data on seemed expressed biological effect of this factor giving the opportunity to develop so-called non-lethal weapons (NLW). Recently published paper of German physicist, J. Altmann on Acoustic Weapons - A Prospective Assessment (2001) has enlightened this part of the issue under consideration.

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Abbreviations

AP	arterial pressure
BBB	blood-brain barrier
BR	breath rate
CACA	continuous accumulation of Coriolis acceleration
CNS	central nervous system
CR	conditioned reflex
CRFC	critical rate of flash coalescence
CST	constant shift of aural sensitivity threshold
dB	decibel
DPC	dynamic pressure chamber
ECG	electrocardiogram
EEG	electroencephalogram
EMF	electromagnetic field
EMR	electromagnetic radiation
GHz	gigaherz
GOST	State Standard
Hz	herz
IS	infrasound
kHz	kiloherz
LFAO	low frequency acoustic oscillations
MHz	megaherz
MPL	maximum permissible level
NLW	non-lethal weapons
PA	phagocyte activity
PAL	phagocyte activity of leukocytes
PNS	parasympathetic nervous system
PR	pulse rate
REG	rheoencephalogram
SanPin	sanitary rules and standards
SHF	super high frequency
SPL	sound pressure level
SSLS	system of standards of labor safety
TST	temporary shift of aural sensitivity threshold
US	ultrasound
VNS	vegetative nervous system
VPC	variable pressure chamber

Introduction

Perhaps the one of first predispositions promoted the problem of specific influence of low frequency acoustic oscillations (LFAO) or infrasound in living organisms was so-called "Wood pipe". Since 1930th they were reported by a number of authors in different books and magazines. When reporting, details and general interpretation was arbitrary changed though, apparently, it was the same event.

This event was the air oscillation source applied in the theatre by Robert Williams Wood, well-known physicist (Seebrook W., 1980): these oscillations were not perceived by spectators. According to reports, the source switched on at the time of the performance has induced strong unexplainable anxiety of spectators who have left the hall. The mass media interpretation of this event has caused two consequences at least.

Firstly, when referring to "Wood pipes", they have attributed some specific health effects, which was the cause of studies to standardize infrasound because of the increased industrial activities resulting to vibration and infrasound exposure.

Secondly, different descriptions of "Wood pipe" effect have resulted to skeptic attitude regarding infrasound health effects; a number of scientists have considered mass media descriptions as a canard and disregarded the possibility of such effects.

However, the interest to the infrasound problem has not been attenuated; moreover, the natural infrasound sources are well known including earthquakes, storms, tsunami, volcano eruptions, rainstorms, wind turbulence, artillery shots etc.

The specific feature of the infrasound is the ability to propagate to large distance from the source without attenuation (large wavelength, small oscillation frequency, significant amplitude, and negligible absorption in the atmosphere and barriers, diffraction) and to "rectify" sounds (harmonics) of aural band because of their large damping.

Infrasound oscillations generated at the sea surface in case of the strong wind ("sea voice") were found due to curls at the sea wave tops. Particularly, it was noted that the human feels this pressure like a tympanic pain. V.V. Shuleykin (1953) has designed the "sea voice" detector to give the storm precaution, because the infrasound velocity is higher than the velocity of storm waves, which are the powerful source of the "sea voice". According to Academician A.N. Krylov (1950), some seacoast organisms leaving the coastal area long before the storm are sensitive to such infrasound storm precautions.

Later on, in addition to initiated hygienic studies, the interest to the infrasound effects was enforced because of attempts to explain

shipwrecks and air plane accidents observed in some areas of the world ocean, which events were accompanied by the enigmas of strange behavior or disappearance of the crew and passengers. Together with very fantastic and doubtful suggestions, the most rational hypothesis was the specific infrasound influence in humans and devices (false operation of relays and automates, deviations or oscillations of measurement device readings, radio communication obstacles) due to the vibration generated by the infrasound in the solid bodies. Such vibration effects in devices are well known for routine conditions.

This problem is under the discussion now with persistent indications to the impossibility of the detailed systematic analysis of accident causes in natural conditions and references to fantastic improbability of the majority of hypothesis; the whole problem is often concluded to be false.

Studies of French researcher, Vladimir Gavreau (Gavreau V., 1965-68) are similar to "Wood pipes"; this researcher has concluded to supposed expressed health effects induced by infrasound generators operated at 7 Hz, which can be correlated to brain θ-rhythm (Bachurina T.I., 1974; Arabadji V.I., 1992) or to the resonance frequency of maximal oscillation movement of human chest and abdomen (Jansen G., 1974; Novogrudsky E.E. et al, 1989).

In 1960^{th} - 1970^{th} researchers of different fields have expressed the interest to the infrasound again. The professional interest to the infrasound has occurred among different specialists including those preparing space ship flights, which crew have to be provided with maximum permissible levels of this factor; hygienic physicians, who did not have sufficient knowledge to regulate low frequency acoustic oscillations in industry and populated environment; acoustic engineers, who had not specially designed measurement equipment for < 20 Hz measurements; other specialists (volcano researchers, oceanologists, seismologists etc.), who is dealing with atmosphere, earth and ocean phenomena including earthquakes, tsunami, volcano eruption, polar aurora and many others.

At that time, the specific infrasound research has been initiated including research in physics, biophysics, engineering, medicine, biology, physiology and hygiene.

The significant milestones for the LFAO research were international colloquiums organized by British Acoustic Society in Sallford, 1971 and by French National Center for Scientific Research in Paris, 1973 (Colloque international sur les infra-sons, Centre National de la Recherche Scientifique - CNRS, Paris, 1973).

Later on, materials of these colloquiums were generalized and published (Tempest W. (Ed.) *Infrasound and low frequency vibration.* London - New York - San Francisco: Acad. Press. 1976. 364 p. and *Colloque international sur les infra-sons*, 24-27 september 1973 organise par le Centre National de la Recherche Scientifique et le Groupement des Acousticiens de Langue Francaise, avec la

participation du Centre National d'Etudes des Telecommunications. Editions du CNRS, (Paris 1974), 435 p.).

Additionally, in 1976, Leonid Pimonow, well known French researcher has published the monograph entitled "Infrasound" [Pimonow L. Les infra-sons. Editions du Centre National de la recherche scientifique (CNRS), Paris, 1976, 277 p.]; so, these events can be the basic endpoint of the initial phase of the infrasound health effect research, which has determined the strategy of followed professional studies.

The initiation of these professional studies has again resulted to periodical scientific publications (since mid 1970th) regarding health effects of low frequency acoustic oscillations and infrasound.

It should be underlined that despite 30 years of studies devoted to infrasound health effects, a number of discussible questions is still exist. These issues include the informative value of LFAO physical criteria, mechanisms of biological effect and whole body reactions, the absence of LFAO effect-frequency ratio, absorption of mechanical energy in biological objects, data transfer from isolated biological objects and model media to human body, etc.

Thus, the search for criteria of the assessment of infrasound as the environmental factor and human health effect inductor is actual and yet unsolved task.

Chapter 1 ACOUSTICS BASICS. INFRASOUND CONCEPT. NATURAL AND ARTIFICIAL SOURCES OF LOW FREQUENCY ACOUSTIC OSCILLATIONS IN THE ENVIRONMENT

1.1 Acoustics. Basic physical concepts

The modern acoustics considers the sound to be elastic media oscillations propagating as sound waves in gaseous, liquid and solid media. According to the definition, the sound oscillations are theoretically in the frequency range of zero to infinity. Depending upon the oscillation frequency, the sound oscillations are purely conditionally subdivided into infrasound, acoustic oscillations and ultrasound (from Latin terms of *infra* (under), *ultra* (further, above) and Greek terms of *akuõ* (to hear) and *akustikos* (related to hearing)).

It is accepted that human is able to hear sound of frequencies of 16-20 Hz to 20 kHz; frequency ranges below 20 Hz and above 20 kHz are not perceptive by the hearing organ. According to the adopted classification, the infrasound is defined as sound oscillations of frequencies below 20 Hz (some researchers sometimes note the upper limit of 16 Hz). The ultrasound is defined as sound oscillations of frequencies above 20 kHz; the frequency range between these limits is defined as the acoustic (i.e. heard) range.

The physical nature of sound, infrasound and ultrasound is the same. The adopted subdivision is determined by the peculiarities of the human hearing apparatus perceptiveness of the specific frequency range only. The limits of the hearing are conditional. It is known that they depend on the individual sensitivity of the sound perceptive apparatus and age dependent peculiarities of the human hearing function.

The basic quantitative feature of the sound is the *sound pressure,* which is the variable portion of the pressure occurred at the time of the sound propagation in the media. When propagating the media, the sound wave creates its inspissations and rarefactions providing additional changes of the pressure if compared to the average value in the media. The sound pressure is changeable with the frequency similar to the sound wave frequency. The measurement unit of sound pressure is Pascal (1 Pa = 1 N/m^2). To provide the measurement comfort the logarithmic scale is used. Besides, the application of logarithmic scale is also preconditioned the logarithmic low of the sound loudness perception (Weber-Fechner law).

The hearing organ distinguishes multiplicity rather than differences of the sound pressure, so the *sound intensity* is adopted as the sound pressure level rather than the absolute pressure magnitude i.e. as the ratio of the created pressure to the pressure accepted as the comparative value. In the hearing range (below the pain threshold) the sound pressure ratios are changed for millions of times so the sound pressure values are expressed via their levels scaled logarithmically in decibels (dB) according to the following formula:

$$L = 20\lg\frac{P}{P_0}, \tag{1}$$

where L is the sound pressure level (dB) (in English literature L is similar to *SPL* (sound pressure level)); P is the measurable average quadratic value of the sound pressure (Pa); $P_0 = 2\cdot10^{-5}$ Pa is the threshold magnitude of the average quadratic value of the sound pressure corresponding approximately to the hearing threshold of the 1000 Hz tone (zero decibel).

The other important feature of the sound is its *frequency* or *spectral composition (spectrum)*. The sound spectrum occurs from the sound decomposition into simple harmonic oscillations. The sound spectral composition is evaluated by the frequency bands. When specifying the continuous spectrum in the acoustic measurement practice, *the octaval* and *1/3-octaval frequency bands* are most often. In the acoustics concept the octave (from Latin term of *octava* (one eighth)) is the of the unit of the frequency range between two frequencies f_1 and f_2, if the logarithm of their ratio is equal to one ($\log_2(f_2/f_1)=1$).

The octaval band is specified by lower, upper and central frequencies. Central frequencies of neighboring octaval bands are two folds different, approximately; the central frequency is determined as the geometrical mean of upper and lower frequencies. 1000 Hz frequency was adopted as the basic central frequency. According to IETC Recommendations No. 225, the preferable raw of central frequencies (f_c) is as follows (Hz): 2; 4; 8; 16; 31.5; 63; 125; 250; 500; 1000; 2000; 4000; 8000 etc. The interrelation between lower (f_l), upper (f_u) and central frequencies for the octaval band is as follows:

$$f_c = \sqrt{f_l \cdot f_u}, \tag{2}$$

$$f_u / f_l = 2, \tag{3}$$

$$f_c = f_l \cdot \sqrt{2}. \tag{4}$$

For 1/3-octaval band these frequencies are correlated as follows:

$$f_u / f_l = 2^{1/3}, \tag{5}$$

$$f_c = f_l \cdot \sqrt[6]{2}. \tag{6}$$

The toneless and discrete spectrum of the sound signal is specified in narrowed frequency bands of 1/12 octave and 3% of the basic frequency as well.

The sound analysis in octaval bands was found comfortable not only due to technical considerations but also due to the peculiarity of the hearing perception: it is known that the hearing analyzer percepts the relative change of the sound frequency rather than absolute one.

The most complete characteristic of the sound is the intensity vector representing the flow density of the sound power (W/m^2):

$$\vec{I} = p \cdot \vec{v}, \tag{7}$$

where P is the sound pressure and v is the oscillatory velocity vector. The sound intensity is the comprehensive magnitude and it is possible to show it as the sum of active and reactive components. The active component of the intensity specifies the sound energy propagating in the space and the reactive component specifies the sound energy non-propagating in the space i.e. the sound energy portion accumulated in the local area of the space. The other sound energy characteristic is the sound energy density (J/m^3), which is equal to the sum of potential, and kinetic energy in the specific point of the space. Human physiology reactions are preconditioned by the very energy characteristics of the noise exposure.

When investigating different acoustic fields, sound pressure measurements do not always provide the complete information on the field peculiarities if the field is of the complex spatial structure. The complete information can be obtained from the analysis of the energy characteristics of the sound field including: the density of potential and kinetic energy and the comprehensive intensity vector. To determine these characteristics, it is necessary to measure three orthogonal components of the oscillatory velocity vector and their phasic relationships despite of the sound pressure measurements.

The determination of integral energy indices of sound oscillations is based upon elements of the theory of the vector fields of the acoustic intensity which theory presumes linear relationships of pressure versus velocity. The concept of this theory has been proposed at 1st International Congress on Acoustic Intensimetry (France, 1981). Basic statements of the acoustic intensimetry follow from the energy conservation law. To get the complete characteristic of the sound field it is necessary to determine 4 magnitudes including: active and reactive intensity component vectors and vectors of potential and kinetic energy density. Generally, the sound field represents the sum of potential (scalar) and solenoid (vortical) fields. The scalar component of the active intensity circulation is always constant, which

certifies to the fact that the energy transfer between two points of the space is only provided by the rotating part of the active intensity vector. The spatial heterogeneity of the sound pressure (i.e. the difference between potential and kinetic energy) is predetermined by interference phenomena and is determined by the reactive intensity component. The rotating part of the active intensity vector will only occur if media particles move via elliptical trajectories.

Thus, the potential component of the active intensity vector determines the direction and the magnitude of the acoustic energy flow irradiated whereas the reactive intensity and vortical component of the active intensity describe the energy exchange between different areas of the sound field (Pascal J.C., 1985; Pascal J.C., Lu J., 1984). The modern intesimeter widely applied to the acoustic measurement practice was created in 1977 only. For the first time (F.J. Fahi), and later (J.Y. Chang) these researchers have independently and practically simultaneously proposed to measure the sound intensity using two microphone probe basing upon modern methods of signal digitizing (Fahy F.J., 1977; Chung J.Y., 1978).

This method should be addressed in more details because it provides more effective solutions for traditional acoustic tasks. These tasks include the measurement of power, propagation direction and localization of noise sources as well as the evaluation of the absorption features of different fences and materials. In some degree, all these tasks have been solving by standard measurements of the sound pressure, which disadvantage consists in the strong dependence of readings versus measurement conditions. To get accurate assessment of the noted values, measurements of the sound pressure level (SPL) should be done inside echo-free or reverberation chambers, which is not always available.

The intensimetry equipment measurement of necessary characteristics is possible in real conditions. This possibility follows from the fact that the intensity is the vector value (by the definition) and SPL is the scalar value. The intensity presentation in the comprehensive form gives the opportunity "to split" the sound energy into two components (active and reactive components). The active intensity component specifies the energy propagating the space and reactive component specifies the non-propagating energy i.e. the energy accumulated in the local area of the space.

This principle was used by Brul and Quer company (System 3360), where the oscillatory velocity value was calculated (Euler equation) via pressure gradient measured in 2 points. If sound fields contain several harmonics or have the random stationary process character, the intensity would be determined via auto spectra or mutual spectra averaged by the ensemble of the signal realizations (Gade S., 1982).

The simplicity and comfortability of the proposed method have stimulated its future improvement to solve a number of acoustic tasks. Since 1978 regular international conferences are arranged to consider intensimetry problems. Standards were developed in the USA, Europe and Russia to regulate the application and to establish the accuracy of intensity measurements (ISO 3740-3746; ISO 140/1-5; ANSI/ASTM S.1 31-36; ANSI/ASTM E 336-77).

Direct acoustic measurements of the oscillatory velocity are not currently practiced because of the absence of the serial equipment. At the same time, when investigating high intensity sound fields (where the oscillatory velocity can reach 0.5 m/s, which corresponds to SPL of ~ 140 dB in the propagating wave), thermoanemometric equipment is more and more applicable.

However, its acoustic measurement application requires the thorough and accurate work on the thermoanemometer probe calibration in reference sound fields (Dragan S.P., Lebedeva I.V., Trifanov V.P., 1986; Lebedeva I.V., Dragan S.P., 1994).

The acoustic measurement practice evaluates sound loudness by the logarithmic scale using the intensity level expressed in decibels (dB):

$$L = 10\lg\frac{I}{I_0}, \qquad (8)$$

where $I_0 = 10^{-12}$ W/m^2 is the intensity of the threshold hearing perception. The particular case of the sound wave intensity basically consisted of the active component is specific to the intensity level which is equal to the sound pressure level expressed via the time averaged quadratic value of the measured pressure ($\overline{P}$) as follows:

$$L = 10\lg\frac{\overline{P}^2}{P_0^2} = 20\lg\frac{\overline{P}}{P_0}, \qquad (9)$$

where $P_0 = 2\cdot10^{-5}$ Pa is the quadratic mean of sound pressure corresponded to the hearing perception threshold.

It is known that sounds of the similar intensity but different frequency would be perceived differently. To assess the sound perception equivalence, curves of similar loudness were drawn and it was found that the ear sensitivity is maximal in the frequency range of 3÷5 kHz and it is minimal in the low frequency range. In case of low pressure levels the difference between maximum and minimum sensitivities is ≈ 90 dB. If the sound pressure is elevated, the similar loudness curves will get smoothed and the difference becomes less than 40 dB. The heterogeneity of the amplitude-frequency characteristic of the hearing perception was compensated in acoustic measurement devices and acoustic analyzers using frequency correction circuits and application of scales A, B, C. To evaluate the aviation noise, they also use the frequency correction scale D. At present, frequency corrections B and C are not practiced and international, national and industrial standards regulate noise parameters applying scale A or linear scale. The noise parameter determined by scale A is named as sound level (L_A, dB) and that determined by linear scale is named as sound pressure level (L, dB). The standard difference between sound pressure level and sound level for a number of octaval bands is given by Table 1.1.

Table 1.1 - Standard difference between sound pressure level and sound level for a number of octaval bands

Central frequency, Hz	16	31.5	63	125	250	500	1000	2000	4000	8000
Correction, dB	80	42	26,3	16,1	8,6	3,2	0	-1,2	-1	1,1

The continuous noise is standardized on sound pressure levels in standard octave bands; the approximate assessment is permitted to be sound level L_A, dB "A", which is determined in the whole frequency band.

The standardized parameters of variable noise include energy equivalent sound levels, L_{Aeq}, dB "A" and maximal sound levels, L_{Amax}, dB "A".

The energy equivalent sound level, L_{Aeq}, dB "A" of the specific variable noise is the sound level of continuos wide-band noise which has the averaged quadratic sound pressure similar to the specific variable noise within the specified time period calculated according to the following formula:

$$L_{Aeq} = 10\lg\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2}\frac{P_A^2(t)}{P_0^2}dt\right], \qquad (10);$$

where $P_A(t)$ is the current average quadratic magnitude of the sound pressure of the noise signal corrected on the "A" frequency characteristic.

The maximal sound level, L_{Amax}, dB "A" is the sound level corresponding to maximal reading of noise rate meter with visual control or to the value of "A" sound excess within 1% of measurement time if automated recorder is used.

Despite the equivalent sound level, when describing and assessing short-time sounds, the acoustic measurement practice often uses the parameter of single noise phenomenon (event) exposition. The equivalent level of sound exposition (LSE) is the level corresponding to the sound energy (dB "A") obtained within 1 s time period, which energy is identical to the actual energy of the short-time sound or noise. LSE, dB "A" is determined according to the following formula:

$$L_{AE} = 10\lg\left[\frac{1}{t_0}\int_{t_1}^{t_2}\frac{P_A^2(t)}{P_0^2}dt\right], \qquad (11)$$

where t_0 is the standard duration equal to 1 s.

For the theory and practice of hygienic regulation of noise the obvious significance belongs to acoustic parameters specifying average sound level within the long period of time. As the basis time period they use day or any other time period specifying the

real technological cycle of human activity. To evaluate the noise factor they determine *the average sound level within long period of time,* which is the average index of equivalent level of sound within long time period for a number of basis time periods within limits of the long period of time:

$$L_{AeqT} = 10 \cdot \lg\left[\frac{1}{N}\sum_{i=1}^{N} 10^{0.1\left(L_{Aeq,T}\right)_i}\right], \tag{12}$$

where N is the number of basis time periods used for the assessment, $(L_{Aeq,T})_i$ is the equivalent level of sound for basis time period i.

The other parameter often applied to get the hygienic regulation and to assess the health harm is the *noise dose* which is the integral energy accumulated within the exposure time. The noise dose is proportional to the energy equivalent sound pressure recorded on the frequency corrected scale "A" and exposure time ($Pa^2 \cdot h$).

In the human hearable range of sounds the hygienic regulation applies the concept of *acoustic noise.* The acoustic noise (hereafter, noise) is the random oscillations of different physical nature, which oscillations are specific to the random changes of amplitude, frequency and other characteristics. In the common life the noise is the any unfavorable sound interfering the perception of speech, music or hindering the work or relaxation. Noises contain sounds of different frequencies and they can be differentiated according to the distribution of levels of different frequencies and character of the general change in the time course.

Depending upon the sound source the noise is specified according to *the spectrum character* as wide band noise and tonal noise.

The wide band noise has the continuos spectrum of the width above one octave. The continuos spectrum of the wide band noise is specific to homogeneous distribution of frequency components in the whole band. Particularly, when amplitudes of the spectral components in all frequencies are the same, such sound is named "white sound".

The tonal noise has the major frequency in the spectrum; in such case the excess of the level in 1/3 of the octaval frequency band above neighboring ones would be 10 dB at least.

The temporal characteristics of the noise can be constant and variable.

If the sound level within 8 working hours is specific to the time course change of more that 5 dB "A" (measurements of temporal characteristic applying "slow" noise meter specified by State Standard of GOST 17187-81 "Noise meters. General technical requirements and test methods") then the noise is *constant*; *the*

variable noise is specified if the change is 5 dB "A" or more. The variable noise can be of three kinds, according to the criteria given by Table 1.2.

Table 1.2 - Kinds of variable noise

Variable noise	Criteria
Varying in time course	Sound level is continuously changed in time
Intermittent	Sound level is step changed (for 5 dB or more) and the periods of constant signal are equal to 1 s or more
Pulse	The noise contains one or more sound signals; each signal has the duration below 1 s and sound levels measured in dB "A" and dB "A1" ("slow" and "pulse" modes of the noise meter measurements according to State Standard GOST 17187-81, respectively) are different for 7 dB at least.

To hygienically evaluate the noise, they use the sound band of 45 to 11,000 Hz including eight octaval bands specified by Table 1.3.

The control of noise contamination of industrial and common life environment and reached regulator achievements has resulted to the change of structure of noise spectra structure, where low frequency oscillations and infrasound are predominant now.

Table 1.3 - Average geometrical and border-line frequencies of octaval bands of noise in the range of 45 to 11,000 Hz

Average geometric frequencies, Hz	Border-line frequencies, Hz	
	lower	upper
31.5	22.4	45
63	45	90
125	90	180
250	180	355
500	355	710
1,000	710	1,400
2,000	1,400	2,800
4,000	2,800	5,600
8,000	5,600	11,200

1.2 Basic physical characteristics of the infrasound and low frequency acoustic field

The infrasound (as it was mentioned above) is the range of acoustic oscillations of the frequency band below human hearing ability. Usually, the upper border-line of the infrasound is 16-20 Hz and the lower border-line is not defined.

The majority of acoustic publications indicate that the hearable frequency band is 16 Hz to 20 kHz. According to the opinion of a number of audiologists, infrasound oscillations do not induce the hearing sensation. However, G. von Bekesy, (1936), N.S. Yeowart et al., (1967) an others, who studied sound perception in the frequency range below 20 Hz, there are evidences indicating to

possibility of the hearing organ perception of infrasound oscillations of different intensity.

Basing upon the data review of N. Karpova and E. Malyshev (1981), the picture of the hearing perception area is shown by Figure 1.1. Its border-lines are as follows: pain threshold (curve 1) representing the lowest sound power inducing the sensation of unpleasant ear scratching (sound "taction") progressing to the pain sensation; and the hearing threshold (curve 2) representing the lowest sound power to be able to perceive by the human ear at this frequency. The Figure demonstrates that human ear is able to perceive sound oscillations of very vide frequency band starting from zero hertz practically and up to one hundred kilohertz for corresponding intensity of these oscillations. However, the normal perception of sound is limited by the hearing are shown.

The ultimate values of the hearing range are cross points of curves of hearing and pain. It is obvious, that the left border-line of the hearing range is the point of the level of sound pressure (LSP) of 140 dB at the frequency of ~ 1.6 Hz, and the right border-line is the LSP point of 150 dB at the frequency of ~22 kHz. Taking into account that these levels of the sound pressure are not practically present in the natural human environment, one can consider that the major range of hearing is 16-20 Hz to 20 kHz.

Practically, all existing classifications of acoustic oscillations are related to the human hearing perception. The conditionality of ranging of acoustic oscillations according to hearing sensations was noted (Gierke H.E. von, 1976 and others). These specialists have considered experimental data (Yeowart N.S., 1976) confirming the possibility for human hearing perception for sounds out of the hearing range if these sounds are rather intensive.

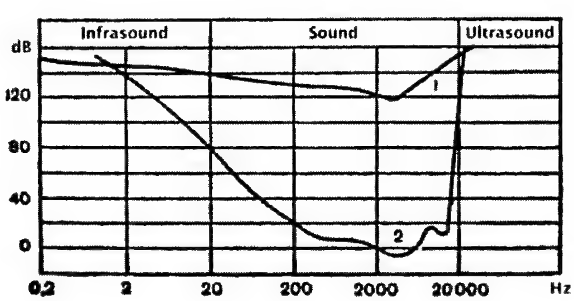


Figure 1.1 - Area of hearing perception (Karpova N. and Malyshev E., 1981)
1 - pain threshold; 2 - hearing perception threshold

According to the valid note of these researchers, the interaction of acoustic oscillations with biological objects is basically

determined by the relationship of geometric sizes of these objects versus the wavelengths of the affecting oscillations. This very relationship determines the ability of manifestations of some wave processes of the mechanic energy transfer predetermining biological effects of acoustic oscillations. If the wavelength exceeds linear sizes of the human or animal body, such oscillations should be referred as low frequency ones (Gierke H.E. von, 1974; Pimonow L., 1976).

Thus, the traditional physiological principle of the frequency attributing of acoustic oscillations according to their audibility can be opposed by the physical principle based upon the relationship of linear sizes of biological object versus acoustic wavelengths. Basing upon this principle, it is convenient to speak about low frequency acoustic oscillations rather infrasounds. This term is mentioned in medical literature since 1970^{th} (Mozhukhina N., 1979; Karpova N., Malyshev E., 1981) and is most rightful when considering the health effects.

The upper borderline of low frequency acoustic oscillations is in the range of 200 to 400 Hz depending upon linear sizes of biological object (Ermolaev V., Levin A., 1969; Gierke H.E. von, 1974). The proposed definition most completely reflects the physical origin of low frequency acoustic exposure which is not only limited by hearing sensations, but also revealed in many reactions of the whole organism (Gierke H.E. von, 1976; Paranko N., Madatova R., 1990).

The specific feature of infrasound waves is the large wavelength due to the low frequency of oscillations and high propagation velocity ($\lambda=c/f$, where $c=330$ m/s is the sound velocity at normal conditions and f is the frequency). Due to the large wavelength, the infrasound the infrasound has better bending ability if compared to hearable sounds and energy loss is negligible in such case. The infrasound is poorly absorbed in the atmosphere and the wave is weakly attenuated for large temperature gradients, when wave guiding occurs; this is the explanation of the infrasound propagation to large distances and the propagation distance is inverse proportional to the frequency.

The other peculiarity of the infrasound is its "penetrative" ability. As a rule, all living premises have their own frequencies in the infrasound range. When interacting the infrasound wave to the living objects, the infrasound field of the own standing wave frequency or the volumetric resonance field is created. The biological aggressiveness of the induced field seemed to be more expressed than for the incident wave. To elaborate the hygienic regulation of the infrasound field formed in the living objects, it is convenient to apply energy parameters, which can be only measured by intensimetry methods. It is predetermined by the presence of the significant pressure heterogeneity (up to 12 dB) when IS field is formed on its own resonance frequencies.

Moreover, the infrasound wave has more peculiarity: when interacting to any object (human body, for instance) the wave penetrates the object without any practical reflection. The absorption coefficient is assessed to reach 50%.

According to the spectral character, the infrasound is subdivided into *wide band infrasound* having the continuous spectrum above one octave and *harmonic infrasound* which spectrum contains expressed discreet components; in the last case the excess of the level in the one of octaval bands would be 10 dB at least.

The temporal characteristics specify constant and variable infrasound if the level of the sound pressure within one minute ("linear" scale at "slow" characteristic) has changed for more that 10 dB, than *constant infrasound* is present; if such change is less than 10 dB than *variable infrasound* is present.

The constant infrasound at workplaces is evaluated according to levels of the sound pressure (dB) in octaval frequency bands of 2, 4, 8 and 16 Hz (31,5 Hz octave represents low frequency noises).

It is applicable to determine levels of the sound pressure in 1/3 octaval bands with average geometric frequencies of 1.6; 2; 2.5; 3.15; 4; 6.3; 8; 10; 12.5; 16 and 20 Hz. The standardized characteristic of the variable infrasound is the general level of the sound pressure (dB) measured in "linear" scale. To assess the infrasound presence, the approximate characteristic of the difference between noise meter readings (dB, "linear" scale) and frequency correction application "A" (dB "A") is applicable. If the difference of levels (Δ) (dB, "linear" scale) is as shown below, the rank of the infrasound is as follows:

- $\Delta < 10$ dB: insignificant;
- $11 < \Delta < 20$ dB: low levels;
- $\Delta > 21$ dB: significant.

Thus, the considered material gives the opportunity to understand that elastic deformation laws are valid for all frequencies oscillations in the air including infrasound ones. Peculiarities of infrasound wave propagation are related to the low frequency of the elastic media oscillations and include:

- much more higher amplitudes of oscillations, if compared to acoustic or ultrasound waves in case of similar power of the sound sources;
- directness of the infrasound emission is principally similar to sound processes;
- infrasound absorption in the atmosphere is less if compared to high frequency sounds, which results to the infrasound propagation to large distances;
- the infrasound propagation to large distances is also determined by the presence of the wave guiding channels in the atmosphere due to the atmospheric heterogeneity;

- the infrasound is different from hearable sounds due to the larger wavelength, so its propagation is more expressed for diffraction;
- infrasound oscillations are able to induce vibration of large objects due to the resonance phenomenon;
- the dispersion of the sound velocity is possible at infrasound frequencies, which is resulted from the adiabatic-isothermal transformation process of sound oscillation.

Physical peculiarities of the infrasound and low frequency acoustic oscillations require the elaboration of new methodological research approaches, the revealing unclean peculiarities of health effects in human and animals as well as the development of preventive and hygienic countermeasures to control the unfavorable exposure.

1.3 Natural and artificial (man-made) sources of the infrasound and low frequency acoustic oscillations

The infrasound or low frequency oscillations of the infrasound band (< 20 Hz) are widely disseminated in the environment. The infrasound is the persistent factor of noises and vibrations naturally occurred due to the turbulence of fluids and gases, at sea storms, tide waves, air flow above mountain areas, earthquakes, volcano eruptions, bolide explosions, polar auroras, strong thunderstorms and seismic events (Shuleykin V., 1953; Novogrudsky E. et al, 1989; Arabadji V., 1992; Leventhall H.G., Kyriakides K., 1976).

The development of modern technologies, transportation and improvements of technological processes and equipment accompanied by the increase of power and sizes of machines has resulted to the significant increase of infrasound components of the environment and their intensity growth. These components are generated at the time of reciprocating movement of parts of different mechanisms and inside operated installations: blast furnaces, diesel motors, forge presses, reactors. The aircraft, space missiles, artillery shots and such powerful sources like nuclear explosions also generate low frequency acoustic oscillations. The option to detect nuclear explosions at far distances using long distance propagation in the atmosphere was the start point of the development of the infrasound measurements and theoretical studies on infrasound radiation propagation (Malyshev N., 1972; Gabovich R., Sanova A., 1977; Reutov O., 1978; Erokhin V., Glinchikov V., 1979; Karpova N., Malyshev E., 1981; Suvorov G. et al, 1979,1983; Evans M.J., Tempest W., 1972; Stephens R.W.B., 1974; Frolov K. et al, 1996).

A number of works (Andreeva-Galanina E., Malyshev E., Pronin A., Skorodumov G., 1970; Ivatcevich I., Klimenkova O., 1975; Klimekova O., Soldatkina S., 1978; Suvorov G., Ermolenko A., Loshak A., 1979; Karpova N., Malyshev E., 1981; Alexeev S., Usenko

V., 1988; Erokhin V., 1976; Maltceva I., Shaypack E., 1981; Suvorov G., 1983; Nedomerkov Yu., 1989, 1990; Cavreau V.R., 1965; Atherley G.R., 1969; Stephens R.W.B., 1969; Tempest W., 1976; Pimonow L., 1976; Cook R.K., Young J.M., 1962; Izmerov N. et al, 1998) has demonstrated that infrasound sources are widespread in the modern industry and transportation and can reach intensity levels of 80–130 dB.

The trend of the increase of infrasound and low frequency acoustic oscillations together with the ability of long distance propagation (significant shift amplitudes, negligible absorption in the atmosphere and shields, diffraction) result to the possible unfavorable exposure in the significant workforce contingents. The infrasound exposure can occur at work and relaxation. Inhabitants of large cities using transportation daily (metro, automobiles, railways) are exposed to the significant dose of noise and ultrasound.

Infrasound oscillations of different intensity are always generated if the elastic media (like gas/air, solid body or fluid) are disturbed. Sea waves hitting the coast not only induce weak seismic oscillations in the land but also change the air pressure with the frequency of ~ 0.05 Hz. Very powerful infrasound waves are generated at earthquakes, volcano eruptions, thunderstorms, mountain landslides, hurricane winds, sea storm, auroras etc. Seas and oceans are the richest natural sources of infrasound oscillations perceived by living organisms. Academician Shuleykin (1953) yet in 1932–35 has examined infrasound oscillations induced by sea waves and named them like "sea voice".

In 1930th Russian researchers (V. Berezkin and V. Shuleykin) made experiments with meteorological probe balloons filled by hydrogen and noted that if they put the ear at such balloon, the pain pulse occurs. It was found that this pain sensation is resulted from strong resonance oscillations of the balloon shell at very low frequencies (8–13 Hz), where sounds are still not hearable. Far from the sea the same probe balloon has not resonated and emitted intensive waves. V. Shuleykin has supposed that when above the sea the balloon has resonated due to the periodical air oscillations resulted from the wind movements above the tops troughs of sea waves. This supposition was confirmed and infrasound (i.e. out-of-hearing) oscillations above the sea were named as "sea voice" (Klukin I., 1984).

Even in case of the still weather when mare winds are absent, the pressure pulsation in turbulent flows can create local noises of the infrasound band (Shuleykin V., 1953; Stephens R.W.B., 1969). The atmospheric propagation of infrasound waves is peculiar as follows: initially, the radiation moves up, changes its direction in ~ 50 km altitude and than, at the distance of 200–300 km from the source it comes back to the surface, reflects and goes up again (Brekhovskikh L., 1974; Khorbenko I., 1978; Vladimirskikh B., 1982 and others).

Infrasound oscillations can propagate large distances in the ground, which is the basis of the seismology.

Hurricanes and oceanic storms are powerful infrasound sources. They occur due the turbulence of fluid and gas flows occurred at sea storms, tide waves (tsunami) (up to 140-145 dB, "linear scale"), air movements above the mountain areas (Shuleykin V., 1953; Arabdji V., 1992), earthquakes, volcano eruptions (up to 155 dB "linear scale"), bolids, polar auroras, strong thunderstorms and other seismic phenomena (Leventhall H.G., Kyriakides K., 1976; Novogrudsky E. et al, 1989; Izmerov N. et al, 1998). The nature of some low frequency acoustic oscillations is not known yet (Gossard E., Hook U. Kh, 1978).

The seismic activity is correlated to the solar activity. It is very probable, that the same solar activity correlation exists for infrasound noise intensification. Infrasound signals generated by polar aurora are tightly correlated to the solar activity. The polar aurora creates LSP of ~ 100-110 dB "linear scale" (Izmerov N. et al, 1998). Magnet storms are accompanied by acoustic infrasound storm with 100% probability (Campbell W.W., Young J.M., 1963; Vladimirskikh B., 1982) and its signals cover the band of 0.05-0.01 Hz.

In the fluctuation spectrum of the atmospheric pressure the infrasound oscillations cover the band of 16 Hz to 0,03 Hz (gravitation waves dominate the lower frequencies). Significant noises are always present in the indicated band and sources of these noises are often unknown. One of causes is the weak attenuation of oscillations of frequencies below 1 Hz. Moreover, the larger wavelength the more significant diffraction phenomenon is expressed. Thanks to that, the infrasound can easily penetrate premises and shields able to stop audible sounds. Infrasound oscillations are able to induce vibration of large objects due to the resonance phenomenon.

The infrasound background of our planet is persistently changeable, which is caused by the persistent energy exchange between different natural phenomena including earthquakes, volcano eruptions, thunderstorms, forest fires, magnet storms etc (Cook R.K, Young J.M., 1962). Recently, the increase of the infrasound background is observed in the environment due to the human activities.

Though the physical nature of the infrasound is similar to that for sound waves of any frequency bands, it was already noted that it has a number of peculiarities giving the long distance propagation and far distance exposure abilities. These peculiarities are basically caused by low frequencies and large wavelengths. In case of infrasound frequencies, wavelengths in the air are 17 m to 34 km, 75 m to 150 km in the water, and 150 m to 300 km in the ground surface. The infrasound attenuation in the environment occurs at the distance from the source and is caused by the energy

absorption in the atmosphere for less than 1%. It is supposed that average constant infrasound background is specific to the sound pressure of 0.001-0.0035 Pa (35-40 dB) in the frequency band of 1-0.02 Hz (Izmerov N. et al, 1998).

The traffic, conditions of the road surface, wind between buildings, door shuts, shaken trees, windmills, lightning etc. are natural sources of super low frequencies (Myasnikov A., 1967). For instance, in the calm weather the recorded infrasound levels are 90 dB in the 16^{th} floor flat, whereas they were up to 117 dB in the windy weather at the frequencies of 1-10 Hz. If atmospheric pressure varies on the frequency of < 1 Hz, infrasound levels reach 100 dB (Table 1.4).

Pressure levels of the natural infrasound (75-95 dB) are rather common. As a rule, natural infrasounds belong to the frequency range of < 0.1 Hz, though they are sometimes recorded at 1 Hz frequency. In the atmosphere the infrasound oscillations are recorded during geophysical processes like volcano eruptions, storms, tsunami etc (Cook R. K., 1975; Klukin I., 1984).

Yu. Gostintcev et al, (1983) have experimentally established that large fires (≥ 1 ha) are the strong natural source of wave atmospheric disturbances. They generate infrasound and internal gravitation waves, which are reliably recorded for a number of other natural foci (volcano eruptions, storm weather, meteorite hit, magnet storms etc).

The infrasound pressure was detected in the aircraft pathways, inside automobiles, trains and vessels, during the operation of the vessel engines, compressors, vibration instruments, fans, air conditioners, powerful turbines of diesel electric supplies, gas turbine installations, Martin furnaces.

It was demonstrated that expressed infrasound exposure is essentially sound when working with automobiles, vessels, trains, tractors and self-propelled machines, dredges, cranes, compressors, furnaces and other technological equipment. In such case the maximal levels of the sound pressure belong to octaves of average geometric frequencies of 8, 16 and 31.5 Hz, and maximal levels themselves vary from 90 to 118 dB, so, if sound levels at such workplaces are 70 to 100 dB "A", the grade of infrasound expressiveness is 5 to 42 dB according to the difference dB "linear scale" versus dB "A". Infrasound oscillations occur at any mechanical oscillation of large surfaces and in case of powerful aerodynamic processes in the elastic media (Izmerov N. et al, 1998; Karpova N., Malyshev E., 1981).

Table 1.4 - Infrasound and low frequency noise in industrial and common life environment (From: von H.E. Gierke and D.E. Parker, 1976)

Sources	Frequency of maximum levels, Hz	Maximum levels, dB linear	Spectrum character	Reference
Wind noise during the storm (last floor of 16 floor building)	< 1	118	sharp	Bruel P.W., Olsen H.P., 1973
Wind noise during the storm (13th floor of 14 floor building)	< 1	120	sharp	Bruel P.W., Olsen H.P., 1973
Atmospheric pressure varying	< 1	100	—	Nixon C.W., Johnson D.L., 1973
Earthquake and volcano eruption noise	10	86	smoothed	Stephens R.W.B., 1971
Blast furnace: loading platform	25	123	—	Leventhall H.G., 1974
Vibration instruments: foundry shops	25	120	—	Leventhall H.G., 1974
Industrial compressor	25	114	smoothed	Leventhall H.G., 1974
Blast furnace	7	115	sharp	Leventhall H.G., 1974
Noise in the separated premise of the boiler-house	41	89	sharp	Leventhall H.G., 1974
At 20 yards from manual operated drop hammer	30	82	plain	Stephens R.W.B., 1971
Ventilation system noise: industry laboratory administrative premises	 20 33 30	 86 91 78	sharp	Leventhall H.G., 1974
Agriculture tractor noise	2,4 and 30	80	plain	Stephens R.W.B., 1971
Diesel train noise	2–32	100	plain	Leventhall H.G., 1974
London metro noise	20	90	plain	Stephens R.W.B., 1971
Vessel noise: Machinery deck Control room 1st class passenger rooms	 15 8 32	 133 103 110	sharp	Leventhall H.G., 1974
BAC 1-1 airplane noise: At take-off Inside the flying plane	 6 and 30 < 10	 75 120	 plain -	Stephens R.W.B., 1971
Helicopter noise: 2 seats helicopter 5 seats helicopter	 15 28	 118 120	sharp	Tempest W., 1971
Inside space ship	1–20	145	-	Leventhall H.G., 1974
Large missiles	1–20	150	-	Tempest W., 1971
Inside submarine	5–20	140	-	Tempest W., 1971
Inside automobile with _ open windows at 100 km/h	2	115	smoothed	Leventhall H.G., 1974
Same but with open back windows	16	112	sharp	Leventhall H.G., 1974
Volvo car at 100-110 km/h with half open windows	< 1	117	sharp	Bruel P.W., Olsen H.P., 1973
FIAT-500 with open sunroof	< 1	107	sharp	Bruel P.W., Olsen H.P., 1973
Inside taxi car: closed windows open windows	 3 and 13 28	 95 92	plain	Stephens R.W.B., 1971
Running	2 - 4	90	-	Nixon C.W., Johnson D.L., 1973
Swimming	0,3 - 0,7	140	-	Nixon C.W., Johnson D.L., 1973

1.3.1 Industrial infrasound oscillations

The application of different machines and mechanisms, the increase of their power and sizes, their productivity and other technical characteristics result to the trend of the increase of the low frequency components of noise spectra at workplaces and infrasound occurrence as well.

The infrasound is still poorly investigated occupational factor able to make the unfavorable influence in health and workability (Andreeva-Galanina E. et al, 1970; Reutov O., 1978; Tempest W., 1976; Pimonow L., 1976; Sanova A., 1977; Suvorov G. et al, 1979; Karpova N. et al, 1972; 1973; 1976; 1979; 1981; Alexeev S. et al, 1980 and others).

It is known from literature that air media oscillations submit to aerodynamic laws. The specific feature of the infrasound is the large wavelength and law frequency if compared to the audible sound and ultrasound. In such case infrasound waves can easily bend shields and well propagate air media to the long distances with insignificant energy loss, because the atmospheric absorption of the infrasound is insignificant and equal to $8 \cdot 10^{-6}$ dB/km (Cook R.K., Young J.M., 1962). These peculiarities impede the infrasound control, because the classic methods (sound absorption, sound isolation, and source removal) are effective for high frequencies only.

A number of publications note that modern industry and transportation involve infrasound sources like compressors, air conditioners, turbines, industrial fans, oil injectors, vibration instruments, blast and Martin furnaces, heavy machines with rotating parts, engines of airplanes and helicopters, diesel engines of vessels and submarines, and terraneous transport as well (Malyshev E., 1973; Karpova N., Malyshev E., 1981; Evans M., Tempest W., 1972; Stephens R.W.B., 1974; Leventhall H.G. 1974; Kyriakides K., Leventhall H.G., 1977 and others).

The industrial infrasound represents the portion of the mechanical energy generated by different equipment and it occurs in case of the movement of large surfaces, powerful turbulent flows of fluids and gases, shock excitation of constructions, rotary and reciprocating movement of large masses with repetition of cycles of 20 times/s at least. Many spectra of industrial and transport noises contain infrasound components, which are not detected by routine measurement devices and have high levels of the sound pressure (Zinchenko V., Grigorian F., 1964; Zakharov L. et al, 1977; 1980; Malyshev E, 1973; Kyriakides K., Leventhall H.G., 1977).

The infrasound measurements done in metallurgy plants have demonstrated that levels of sound energy of 115-118 dB at frequencies of 6-12 Hz were found near blast and steel furnaces. At the workplaces the infrasound levels were 97-100 dB in 16 and 31.5 Hz octaves (Martin furnace operator), 100-105 dB at frequencies of 12.5 and 16 Hz (electric melting shop), 107 dB in

16 Hz octave (forge stamping shop during steam hammer operation) (Reutov O., 1975; Erokhin V., 1976; Stephens R.W.B., 1974). Authors have noted that the infrasound levels were higher in premises near-by to heating furnaces if compared to the source place (102-105 dB at 8-12.5 Hz frequencies).

Hygienic studies (Shaypack E., 1981, 1983; Brinza V., Podlevskikh M., Slobodyanik T., 1992) have also demonstrated the wide dissemination of this factor in metallurgy. The infrasound is the integral part of noise spectra emitted by technological installations. Low frequencies dominate in noise spectra at the majority of black metallurgy equipment.

N. Izmerov et al (1998) have indicated to three major types of spectra as follows: infrasound spectra, where maximal levels of the sound pressure are in octaval bands of average geometric frequencies of 2-26 Hz; infrasound low frequency spectra, where maximal levels of the sound pressure are in octaval bands of average geometric frequencies of 2-125 Hz; and low frequency spectra, where maximal levels of the sound pressure are in octaval bands of 31.5-125 Hz. The majority of noise spectra at metallurgy workplaces are of infrasound low frequency character. Pure infrasound spectra are specific to premises where infrasound sources are absent as well as for compressor stations equipped by piston compressors. Particularly, the noise spectra of named machines have maximal levels of the sound pressure at 100-135 dB (Table 1.5).

Table 1.5 - Workplace classification for transport means and technological equipment according to noise characteristics of the infrasound band (from Izmerov N. et al, 1998)

Spectrum character	Octaval bands with maximal levels of the sound pressure	Machines and equipment
Infrasound	2, 4, 8, 16 Hz; 82-133 dB	automobiles, blast and oxygen converting furnaces, river and sea vessels, trains, compressors
Low frequency infrasound -	2-125 Hz; 84-112 dB	Martin furnaces, some kinds of transport vehicles, self-propelled and semi-stationary machines
Low frequency	31.5, 63, 125 Hz; 84-116 dB	Electric arc furnaces, drive trucks, caterpillar tractors, port cranes, turbine installations, loading trucks, dredges

The industrial infrasound oscillations of the range of < 20 Hz are generated by air and piston compressors with maximal levels of the sound pressure of 92 to 123 dB in 8-16 Hz octaves, basically (Klimenkova O., 1977; Sanova A., 1976, 1977; Malyshev E., 1973; Karpova N., Malyshev E., 1981; Stephens R.W.B., 1974).

The infrasound measurements in compressor shops (operation control panel) have demonstrated that noise spectrum generated by piston compressors has the peak in 1/3 octave of 20 Hz with infrasound delta of 23 dB. Such noise is tonal (the peak excess

above neighboring levels in 1/3 octaval bands is above 10 dB), and the noise spectrum character gives the opportunity to consider it as the expressed infrasound one.

The analysis of noise spectra of vibration instruments of 5 and 10 tons load abilities has demonstrated that maximal sound levels are in 32 and 63 Hz octaves and equal to 107 and 123 dB, respectively, with maximal acoustic energy at 50 Hz frequency. Levels of the sound pressure in 2-16 Hz octaves were similar to that in 500-1000 Hz octaves. The spectrum decrease versus 63 Hz octave peak is about 6 dB per octave (to low frequencies) and 10 dB per octave (to high frequencies). The level difference (dB "linear" versus dB "A") is 25 dB, i.e. the noise spectrum generated by vibration instruments has the expressed low frequency character.

Noise measurements at workplaces of turbine hall operators, at control shields, in filtration shops and in premises of compressor stations of the nuclear power plant (NPP) have demonstrated that the noise generated by NPP equipment has the wide band character with acoustic energy of 86-98 dB predominantly in 32-63 Hz octaves and infrasound delta is 10-15 dB. This noise is of low frequency character with infrasound signs present.

Studies elaborated by Stephens R.W.B. (1974), Leventhall H.G., (1976) have demonstrated that infrasound sources can be drainage dams (non-stable water flaw generated infrasound), electric power plant cooling towers (from the falling of the water flow to the reservoir) with 80 dB levels at 10-31.5 Hz frequency band.

The infrasound was also found in noise spectra of the ventilation and air conditioner systems (Table 1.5). For some types of such equipment maximal levels of the sound pressure in 4-32 Hz octaves were 98-100 dB (Karpova N., Malyshev E., 1981). The octaval spectrum of blast furnace fan (1,370 m^3) has infrasound character with maximum LSP of 118 dB in 8 Hz average geometric frequency band, which is above the permissible level for 13 dB (Brinza V., Podlevskikh M., Slobodyanik T., 1992).

1.3.2 Transportation infrasound

Many researchers have demonstrated that transport means are the sources of the infrasound oscillations. W. Tempest (1976) monograph indicates to the fact that transportation is most important area of the infrasound influence in human and society.

H.G. Leventhall et al. (1974) have established that intensive infrasound (up to 118 dB at 7 Hz frequency) occurs in machinery decks of some vessels and 135 dB infrasound of 13 Hz frequency was detected from powerful boat engines. Infrasound oscillation source includes gas turbine installations with combustion chambers and free piston generators (FPG), which are applied as major, auxiliary and emergency engines in ships. The FPG generated noise

is similar to diesel noise but is peculiar by powerful low frequency pulsation of the air at the inflow of piston compressors.

V. Zinchenko and F. Grigoryan (1969) have indicated that the basic frequency of all shocks and hydraulic pulsation specific to FPG is in the infrasound band (8–12 Hz). During the operation of gas turbine installations (with rotor misbalance, essentially), the noise intensity level can reach 130 dB at < 20 Hz frequencies. The noise in the outflow pipeline of these installations is 110–115 dB (at the same frequencies), whereas the noise intensity at > 50 Hz frequencies does not exceed 100–102 dB.

S. Stopsky (1962) has indicated that the powerful turbine operation is specific to the sound energy basically distributed within infrasound band, which is resulted from both the action of pulsed pressure in turbine blades and flow heterogeneity in the working wheel due to the pressure difference on both sides of the blade; he has noted that the turbine oscillation intensity is essentially high in infrasound frequency band.

N. Karpova and E. Malyshev (1981) has indicated that vessel noise is the acoustic oscillations of the wide frequency band from infrasound to ultrasound. The noise source n vessels is the power installations (major and auxiliary engines, diesel generators and rowing electric motors), auxiliary mechanisms (fuel, fire and lubricator pumps, compressors, fans, refrigerators etc), rowing propellers, vibration of vessel corps and its components, wave shocks in the vessel board.

When elaborating acoustic measurements in vessels with underwater wings ("Meteor" type), N. Karpova and E. Malyshev (1981) have found significant levels of the sound pressure in front and rear rooms, control room and upper deck. Highest LSP (110 dB) was recorded in the back room (Figure 8) at 6–10 Hz frequencies. The control room was found to have maximum level of the oscillation intensity at 20 Hz frequency but te general level of oscillation intensity was lower (102 dB). It should be noted that the same premise was found to have the increase of the level of the sound pressure at 8 Hz frequency (up to 99 dB). The front room was noted to have the domination of sound energy at 8 Hz frequency (107 dB). In the upper deck the maximal value of the sound pressure level (105 dB) was in the frequency band of 20–31 Hz.

When analyzing noise records done in St.–Petersburg metro, it was found that moving electric trains are low frequency oscillation generators. The noise spectrum is dominated by very low frequency component. Maximum level of the sound pressure as found in the driver room in octaval bands of average geometric frequencies of 2 and 4 Hz (105 and 104 dB, respectively). The sound pressure level is strongly decreased at middle frequencies.

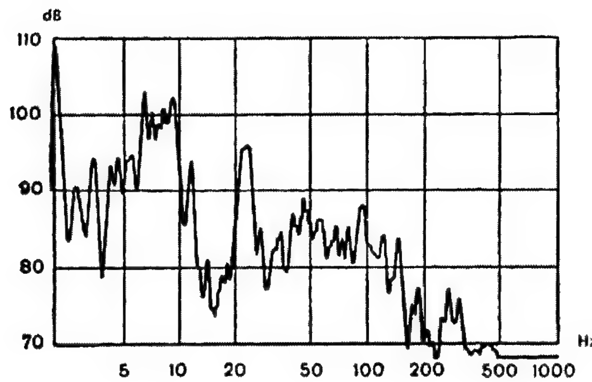


Figure 1.2 – 1/3 octaval noise spectrum in the rear room of the vessel with underwater wings ("Meteor" type) (Karpova N., Malyshev E., 1981)

The noise spectrum for the last car of the electric train is similar to the driver room. The difference consists in the insignificant decrease of the general sound pressure level (for 2 dB) and in the increase of the energy input in the middle frequency band. The maximal value of the sound pressure level was found for first octaval band.

The noise recorded at the metro platform during the train waiting period has low levels of the sound pressure but its spectral composition is similar to that at the time of the train moving. Sound energy maximum is at 2 Hz frequency (79 dB). The comparative recording of noise spectra in underground and ground platforms has not revealed the significant difference of spectra.

Noise examinations inside moving Volga M-1 automobile was done at 80 km/h. The infrasound spectrum components have significantly higher intensity levels if compared to acoustic band components. When moving with closed windows, the general level of the sound pressure was 108 dB inside the car. Peak values are at 8 and 16 Hz frequencies (105 and 104 dB, respectively).

Starting from 31.5 Hz octaval band, the decrease of the sound oscillation intensity has occurred (for 10 dB per octave). 2 and 4 Hz frequencies have also provided the large input to the general intensity level if compared to middle and high frequencies. If one side window is open, the sound pressure levels are increased for 8-9 dB in 2-16 Hz frequency band. The general level of the sound pressure is 116-117 dB and 114 and 113 dB at 8 and 16 Hz frequencies, respectively. The increase of the sound pressure in other octaval bands is not so significant. If both side windows are open, the general spectrum is not seriously changed if compared to previous one. Measurements done at 60 km/h have demonstrated

that the general level of the infrasound pressure is similar to that found for 80 km/h speed. The difference is 2-3 dB in average.

L. Zakharov et al (1977), V. Dokuchaev, Yu. Zaslavsky (1977) and others have also indicated to the emission of low frequency noise of automobile transportation. L. Zakharov et al have provided the infrasound power spectrum inside the automobile moved at 100 km/h. The maximal infrasound level is in 9-12 Hz band.

O. Klimenkova, S. Soldatkina (1977) have provided results of infrasound measurements for automobile and rail transportation (railroads and ground metro stations), and civil aviation. In highways of intensive traffic 65-75 dB infrasound levels at 3.15 to 40 Hz frequencies were recorded. Highest levels were found at the audible spectral band (63-125 Hz) - 80-85 dB. In above-ground motorways and under them 70-75 dB infrasound levels were found and 72-84 dB "A" were found in tunnels. Metro electric trains and railroad electric trains result to 62-75 dB infrasound levels.

The infrasound oscillations were also recorded for aviation and space flights. All transportation systems including jets and, essentially, supersonic jets, missiles, powerful engines used for the space flights generate high levels of infrasound and audible sound.

Infrasound and low frequency noise sources are the turbine and compressor of the jet engine. O. Klimenkova, S. Soldatkina (1977) have established that take-off of turbojets (Tupolev-104, -134, -154) corresponds to the gradual increase of infrasound levels to 70-80 dB at 4 Hz and to 87-90 dB at 20 Hz. Audible component has the peculiar shape with peak energy at 125-250 Hz.

The space ship engine operation in the ground correlates to maximal low frequency noise energy at 1 to 100 Hz. At the take-off the noise and infrasound have long distance propagation to the environment and people in the ground and in the ship are affected to significant levels of low frequency oscillations.

G. Kaschak et al (1970) have investigated long-distance infrasound generated by missiles started from Kennedy cape. The sound energy during ignition and start is distributed in the wide band from 4 Hz to audible frequencies with peak energy at 8 to 16 Hz. Solid fuel missiles have higher initial acceleration if compared to fluid fuel missiles. The full width of the frequency band is 0.1 to 2 Hz for fluid fuel missiles with dominating energy at 0.1 to 1 Hz. For solid fuel missiles the frequency is higher. Authors have recorded early signals at minutes 16-30 after start and late signals started ~ 2 hours thereafter the start.

Thus, the studies demonstrate that transportation means are low frequency oscillation sources, which noise spectrum is dominated by infrasound and rarely exceeds dB levels of sound pressure in middle and high frequency bands.

Studies elaborated by a number of authors on the hygienic assessment of industrial noises give the opportunity to conclude that the noise spectra generated by a number of machines,

technological equipment and transportation means are specific to high levels of infrasound components. The sound energy maximum in such case can be in 2 to 20 Hz frequency range, which depends upon the mode of operation, power, sizes, working frequencies etc.

Sound pressure levels in the infrasound frequency band usually do not exceed 100 dB but the multiplicity of industrial and transportation infrasound oscillation sources certifies to the fact that large occupational contingents of different professions are exposed to their emissions and the issues of the health protection should be considered taking into account the protection against the unfavorable effects of the infrasound.

Literature reference materials on low frequency acoustic characteristics of the workplace of major transportation means and technological equipment are presented by Table 1.6.

Figure 1.3 represents spectral characteristics of the infrasound at workplaces of transport means and technological equipment. The Figure indicates that octaval spectra of the infrasound are rather plain and their hygienic significance is maximal in 8 and 16 octaves if compared to the approximate reference spectrum.

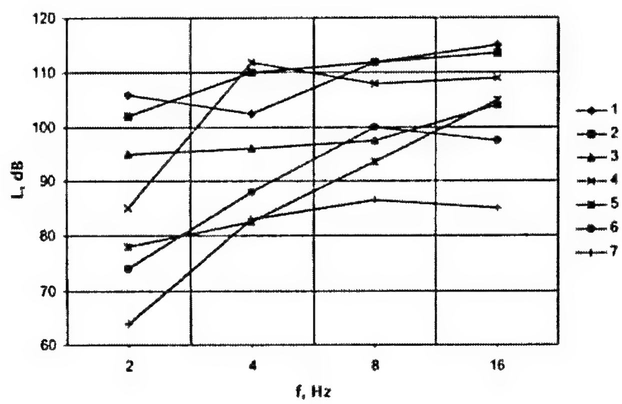


Figure 1.3 - Spectral characteristics of the infrasound (Izmerov N. et al, 1998)
1 - automobiles, 2 - agriculture and construction machines, 3 - semi-stationary equipment, 4 - stationary equipment, 5 - aqueous transportation, 6 - railroad transportation, 7 - communal sources

Table 1.6 – Workplace noise levels for transportation means and transportation technology equipment (from Izmerov N. et al, 1998)

Transportation means and transportation technology equipment	Octaval bands with maximal levels, Hz	Maximal levels in octaves, dB	General level of the sound pressure		
			dB "A"	dB "lin."	Δ
Automobile transport					
ZIL-157 truck	31.5; 63	119; 118	96	119	23
Tatra-148 truck	8; 16	109; 110	85	108	23
ZIL -130 truck	8; 16	115; 116	85	121	36
GAZ-51 truck	8; 16	107; 109	85	109	24
GAZ-53A truck	8; 16	112; 110	84	111	27
KamAZ truck	8; 16	114; 116	82	122	40
GAZ-24 «Volga»	8; 16	115; 113	74	116	42
Shkoda-Alka trailer	2; 16	110; 108	87	106	19
Ikarus-255 bus	8; 16	111; 113	74	102	28
Ikarus-235 bus	8; 16; 31.5	110; 112	76	113	37
RAF minivan	16	98	82	104	22
Aqueous transport					
River transport vessel	16	108	72	109	37
Sea tanker (control room)	16; 31.5	91; 92	61	94	33
Sea tanker (machinery deck)	16; 31.5; 63	101; 98	100	105	5
Atomic icebreaker (control room)	8; 16	115; 118	–	–	–
Railroad transport					
Metro electric train (driver room)	8; 16; 31.5	93; 92	86	95	9
Suburb electric train	8; 16	101; 98	82	104	22
Industrial equipment					
Electric steel melting furnace	31.5; 63; 125	104; 110; 114	104	116	12
Electric arc furnace	63; 125	105; 104	101	108	7
Blast furnace	16	94	87	98	11
Martin furnace	16; 31.5	97; 102; 100	87	100	13
Oxygen converted furnace	8; 16	96	80	101	21
Piston compressor	16	110	83	112	29
NPP compressor station	4; 31.5	82; 84	67	90	23
Air supply chamber	4; 8; 16; 31.5	104; 108	76	110	34

The provided data certify to the fact that spectral content of low frequency acoustic oscillations is heterogeneous. Some transportation means, machines and technological equipment generate maximal levels of acoustic energy in the range of infrasound frequencies and others do the range of low frequency noise, but the mixed infrasound low frequency spectral character is present for some equipment too. It is of great importance for scientifically justified regulation.

Basing upon above mentioned considerations, low frequency acoustic characteristics of workplaces of operators of transportation means, machines and technological equipment can be subdivided into infrasound, infrasound of low frequency and low frequency classes.

The selected spectral classes cover major kinds of jobs of operators exposed to low frequency acoustic oscillation, provide the opportunity to consider their peculiarities when doing hygienic regulation. The classification indicates to the necessity of differentiated approaches and methods to assess the unfavorable effects of low frequency acoustic oscillations of, and indicate to the

necessity of differentiated approaches and methods to assess unfavorable effects of low frequency acoustic oscillations of infrasound, low frequency and low frequency infrasound ranges.

According to N. Izmerov et al (1998) the general level of the sound pressure is as follows:

- in metallurgical industrial premises at workplaces of operators of blast furnaces, oxygen converted furnaces: 98,5±1,9 dB "linear scale" and 78,3±3,9 dB "A";
- near-by the compressor equipment: 96 dB "linear scale" and 64-86 dB "A";
- in some kinds of river and sea vessels: 106 dB "linear scale" and 73 dB "A" and 10-13 dB above standard level in some types of vessels in 8.16 Hz octaves;
- in some kinds of railroad transportation: 104 dB "linear scale" and 82 dB "A";.

1.3.3 Infrasound in living and public premises

Despite the infrasound exposure of automobile drivers and passengers, some automobiles and traffic flows generate the low frequency noise around the roads (Figure 1.4).

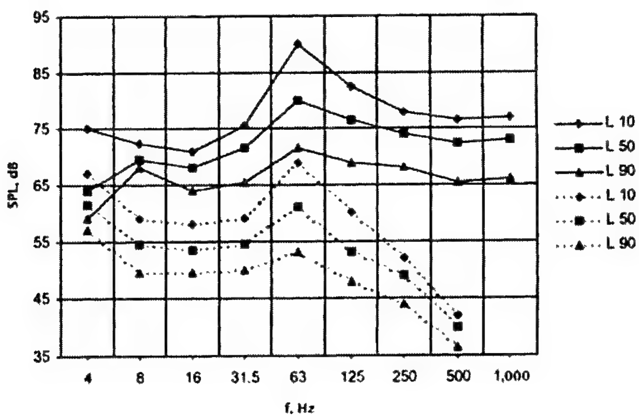


Figure 1.4 - Indoor and outdoor infrasound (Leventhall H.G., 1973; Kyriakides K., 1976)
——————— indoors,
- - - - - - - outdoors

Noise levels measured indoors at 27 m distance from the truck (30 tons weight) are specific to three peaks in the range of 4, 10-16 and 63 Hz. Levels of the sound pressure in these peaks are 60, 71 and 75 dB, respectively. The noise generated from large traffic flow is usually specific to two peaks at 63 Hz (heavy truck movement)

and 125 Hz (high speed traffic). When measuring the noise of traffic flows outdoors and indoors the peak of 90 dB at 63 Hz was separated for the house with double windows. The comparison of data obtained from indoors and outdoors measurement, the difference of levels at sound frequencies was 20-50 dB and less than 10-15 dB at infrasound frequencies.

The noise analysis in administrative buildings of the shaft placed at ~ 100 m from the compressor station has demonstrated that maximal values of levels are concentrated in infrasound frequency band. The grade of the infrasound expressiveness determined by the difference between dB "linear scale" and dB "A" has reached 42 dB, but the general level of the sound pressure was decreased ad equal to 45 dB (dB "A") and 87 dB (dB "linear scale"), i.e. the absence of the infrasound attenuation was found on the background of the decrease of the levels of sound pressure in other parts of the spectrum. These levels should be assessed taking into account the fact that maximum permissible noise levels at administrative workplaces as well as at work of creative character and other intellectual jobs are significantly lower.

The special studies done to assess the infrasound dissemination have demonstrated that sources of the infrasound noise of 109 dB level with maximal acoustic energy in octaval band of 16 Hz average geometric frequency generate infrasound field of 88-93 dB intensity levels at 400-500 m radius. In such case, the indoor infrasound levels are less than outdoor ones for less than 2 dB.

Levels of the infrasound and low frequency noise from industrial and non-productive sources are shown in correspondent tables according to Russian and foreign authors.

Summing up data provided, it should be noted that infrasound oscillations are present at 90 to 135 dB levels (for industrial activities), 70 to 120 dB (in living and public premises), and 80-100 dB (outdoors in the living area). Their expressiveness in the integral noise spectrum is determined by delta (dB "linear scale"-dB "A"), which is 10 to 20-30 dB, i.e. the revealed infrasound was assessed to be in the insignificant to expressed range. In the majority of cases, the infrasound is not present in isolated form but is combined to low frequency noise and vibration.

The elaborated analysis (Izmerov N. et al, 1998) of the man-made infrasound sources (levels and frequency features) has given an opportunity to select several basic groups including automobile, aquatic and railroad transportation; agriculture and construction machines; dredges, compressors, turbines and boilers; metallurgy equipment (electric furnaces); vibration instruments.

It should be noted than the spectral content of low frequency acoustic oscillations is heterogeneous. Some machines and technological equipment generate maximal levels of acoustic energy in the range of infrasound frequencies and others do the range of low frequency noise, but the mixed infrasound low frequency

spectral character is present for some equipment too. It is of great importance for scientifically justified regulation and development of preventive measures, particularly, when developing hygienic requirements for protection against unfavorable effects of these oscillations. This frequency range of the noise can be subdivided into infrasound, infrasound of low frequency and low frequency classes (see Table 1.5). The selected spectral classes cover major kinds of jobs of operators exposed to low frequency acoustic oscillation, provide the opportunity to consider their peculiarities when doing hygienic regulation, and indicate to the necessity of differentiated approaches and methods to assess unfavorable effects of low frequency acoustic oscillations of infrasound, low frequency and low frequency infrasound ranges.

Chapter 2 TECHNICAL SUPPORT OF MEDICAL BIOLOGICAL STUDIES OF THE LOW FREQUENCY OSCILLATION EXPOSURE IN HUMAN AND EXPERIMENTAL ANIMALS

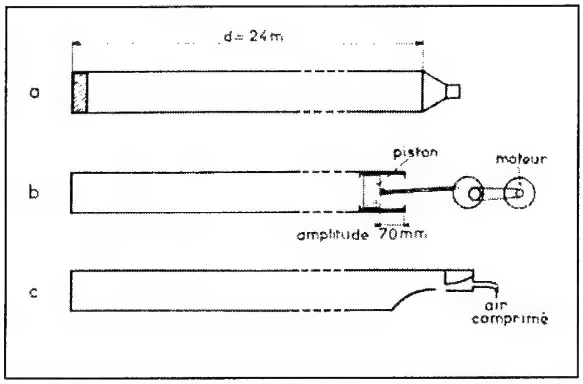
2.1 History of the creation of first generator equipment to research infrasound health effects

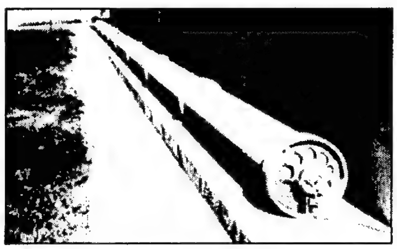
The problem of the generation of infrasound oscillations of different power without high frequency noises exists for a long time and currently it is of great importance for science and technology. In this context, first researches done at experimental conditions are of the exclusive interest.

The peculiar feature of the man-made excitation of infrasound oscillation pressures propagated in the free air consists in the fact that the sound wavelength would increase to several tens - hundreds of meters, when the sound wave frequency is decreased. To generate such waves the routine sound generators are not applicable. The cause of this finding is the large incompatibility of the sound oscillation emitter versus sound waves generated. Due to this incompatibility, the magnitude of the active radiation resistance at low frequencies is decreased and the reactive resistance is increased, which affects the sound power of the emitter. However, the reactive resistance increase does not induce the sound energy emission but causes its transfer from the source to media and vice versa.

One of simplest infrasound generators is the resonance tube where air oscillations are excited; it is rather unwieldy construction. Resonance tubes of correspondent length and thickness give the opportunity to generate infrasound of the specific power. To excite air in the tube, different appliances can be used including electric speaker, pistonphone, organ tip. The frequency control is arranged via tube length change. The disadvantage of such tube is low power as well as large sizes and poor control property (Gavreau V. et al., (1966) CNRS (Centre National de la Recherche Scientifique) Acoustic Laboratory, Marseilles). Principal schemes and photos are given by Figure 2.1.

The other type of the infrasound generation is "whistle" generation (Gavreau V., 1965). The generator was rather powerful but the power control was difficult as well as the frequency control. Whistle generator photos are given by Figure 2.2.

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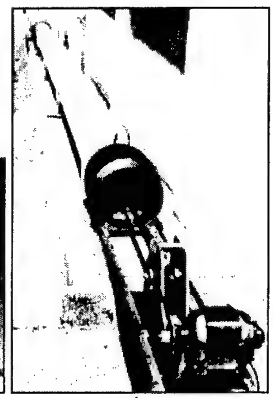
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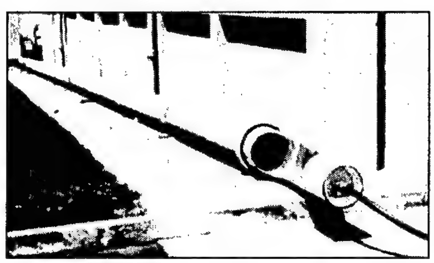
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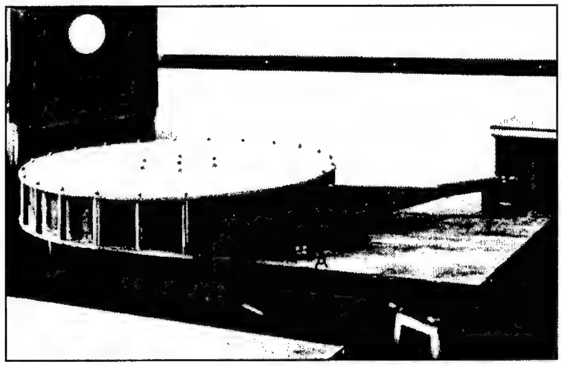
Figure 2.1 - Principal schemes and exteriors of infrasound resonator generators (Gavreau V., Condat R., Saul M., 1966)
a - electrodynamics (semi-undulant) generator of 7 Hz frequency;
b - piston generator c - pneumatic (gas flow) generator of 2.5 Hz frequency



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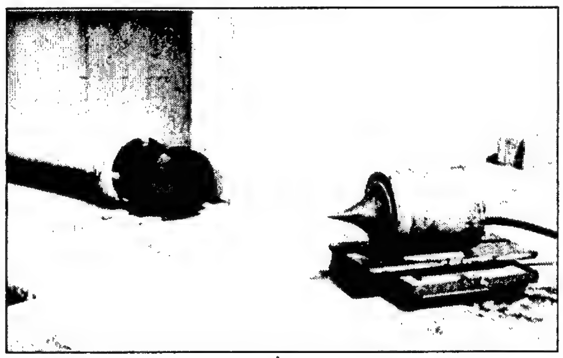

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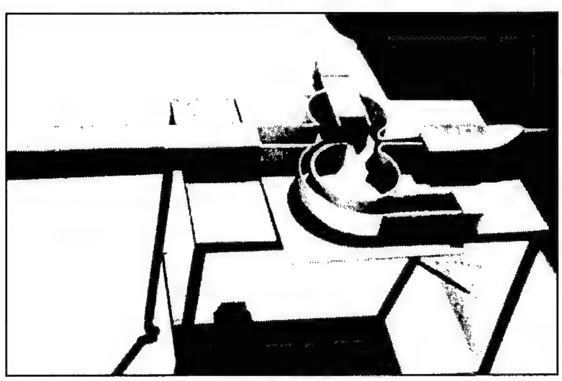

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Figure 2.2 - Infrasound generators of whistle principle
(Gavreau V. et all, 1966)
a - «policeman» whistle generating 37 Hz; b - Galton whistle; c - Lavassseur whistle

The first analysis of existing options for infrasound frequency excitation has caused the development of installations simulating the acoustic wave exposure in biological objects. The simulation essence consists in the changeable pressure created similarly to acoustic wave pressure change in the closed compartment.

The task is considered in quasi static approximation because of the sound dissemination time inside the body, which time is much less than oscillation period.

The mechanical excitation of the air oscillations is most applicable for close compartments (test chambers). It is difficult to obtain large infrasound intensities in such chambers. The volume of the chamber should correspond to the purpose but its sizes should not exceed a quarter of the wavelength related to upper border-line frequency of oscillations excited. This condition is necessary to prevent undulant phenomena occurrence. Otherwise, the heterogeneity of oscillation pressure level distribution should be taken into account.

The chamber construction should be rather strong to prevent the signal contortion and to provide isolation against noises.

These ideas were the basis for infrasound installations developed in Russia and abroad (Karpova N., Malyshev E., 1981; Pimonow L., 1974). Figures 2.3-2.7 provide schemes and photos (from: Pimonow L., 1976).

Figure 2.3 - Dynamic pressure chamber
(Shepherd L.J., Sutherland W.W., 1955)

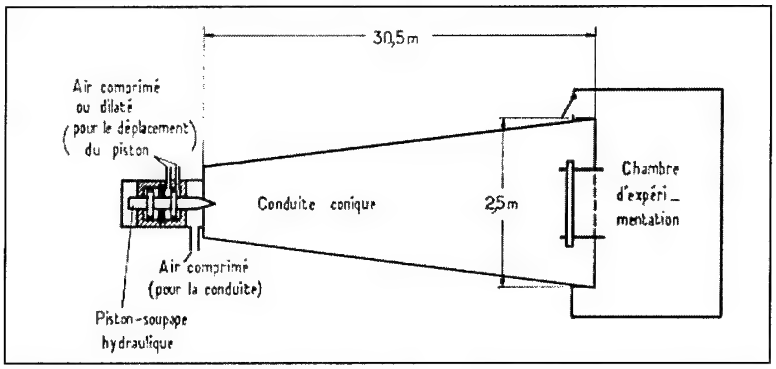


Figure 2.4 - "Bang" type GASL-NASA generator scheme
(Tomboulian R., 1966)

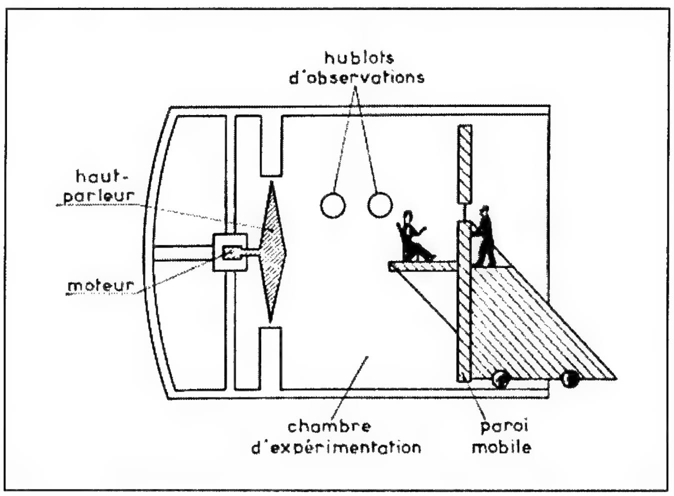


Figure 2.5 - Cylindrical piston chamber scheme (7.3 m diameter, 6.4 m length) to generate infrasound oscillations of sound pressure levels of up to 160 dB at < 3 Hz frequency band (Edge P.W., Mayes W.H., 1966).

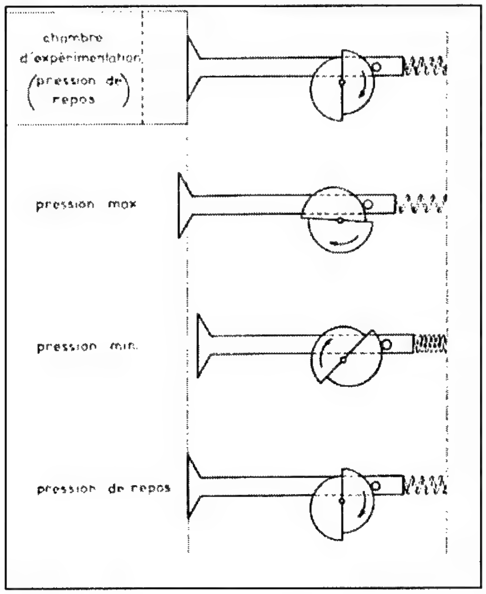


Figure 2.6 – Generation scheme in "Bang" type generator
(Lukas J.S., Kryter K.D., 1968)

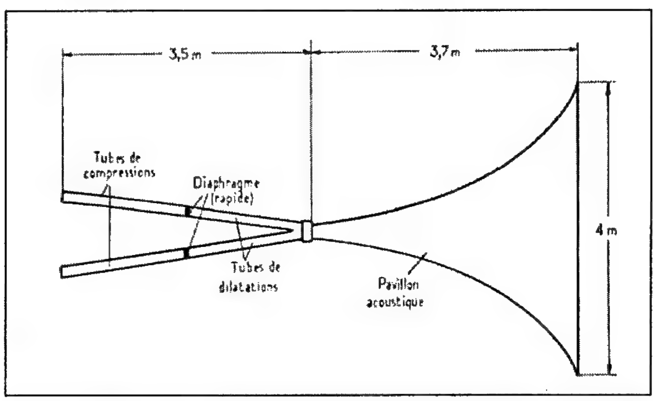


Figure 2.7 – Scheme of pneumatic (aerodynamic) "Bang" type generator
(Dahkle H.E., Kantarges G.T., Siddon Th.E., Van Houten J.J., 1968).

To make experimental physical and physiological studies CNET (Centre National d'Etudes des Telecommunications) has constructed the system of the following parameters (Pimonow L., 1976):

Method of oscillation generation	Frequency, Hz	Intensity level, dB "A"
electrodynamic	3 - 30	max 135
piston	0 - 15	max 192

This system is different from that developed by H.E. von Gierke (1974), where maximal levels of sound pressure were at the level of 172 dB. Principal scheme of Pimonow installation is given by Figure 2.8.

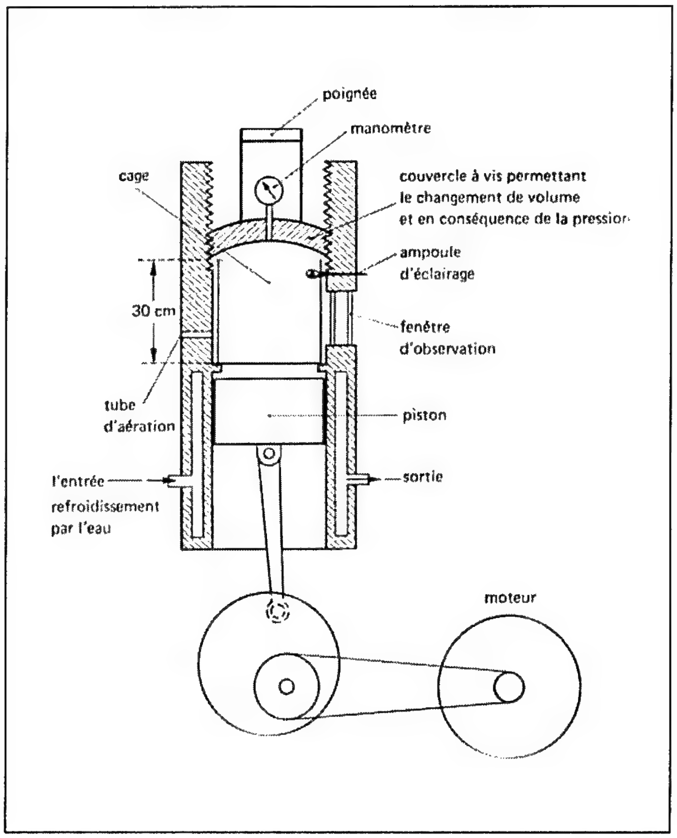


Figure 2.8 - Principal scheme of the dynamic pressure chamber of CNET acoustic laboratory (Pimonow L., 1976)

Due to the small inner volume, the installation was only applicable for small experimental animals (rats. The increasing temperature (due to the piston frictions) was compensated by water cooling. Infrasound frequency is regulated by the rate of electric motor rotations. The increase of sound pressure level was done via wooden bars and the decrease was provided via tap communication to the environment. Levels were as follows: 196 dB (maximum) and 160 dB (minimum).

G.C. Mohr et al, (1965) have done studies in 142 m^3 chamber. The turbojet engine and other real noise sources were used.

Figure 2.9 demonstrates the chamber of B.R. Alford et al, (1966) to measure human physiological reactions to < 22 Hz sound oscillations. Sinusoidal oscillations were generated by pistonphone powered by electric motor. The infrasound intensity was 119 to 144 dB. Figure 4 demonstrates self-lubricated piston moved in 23 cm diameter cylinder electromagnetic valve is present to switch off the chamber by examined person.

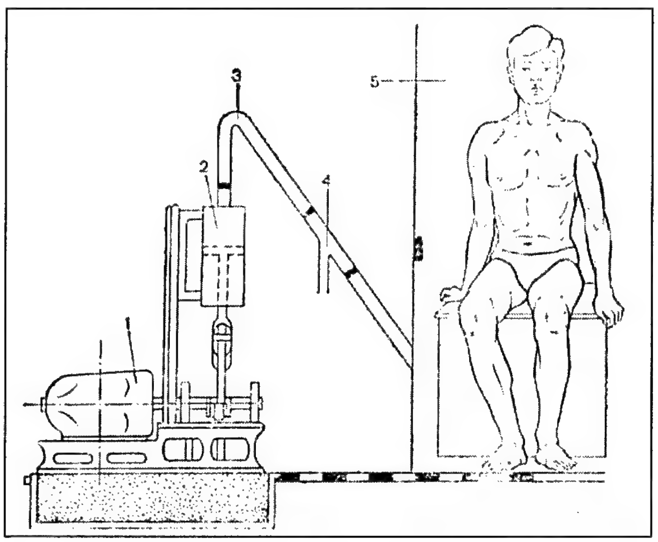


Figure 2.9 - B.R. Alford infrasound experimental installation scheme (1966)
1 - electromechanical drive; 2 - piston transformer; 3 - wave guide;
4 - electromagnetic valve; 5 - test chamber (from: Karpova N., Malyshev E., 1981).

The testing chamber is made of sound isolating materials (wooden shields) with outside cover of duralumin and inside cover of sound absorbing material of 50–100 mm thickness. The observation window is in the chamber door. Authors have indicated that harmonic oscillation contortions were < 2%. The excited signal had sinusoidal shape.

Figure 2.5 demonstrates the experimental installation scheme created by P.M. Edge, W.H. Mayes (1966). The major part is the cylindrical compartment of 7.3 m diameter and 6.4 m length. One side of the chamber is equipped with 4.3 m diameter piston with hydraulic drive controlled by the computer. The other side is covered by moving wall to make acoustic adjustment. Infrasound oscillations had sound pressure levels up to 160 dB at < 3 Hz frequency band.

R. Rocache (1971) experimental chamber is shown by Figure 2.9 (1st variant). It is consisted of generator (pneumatic device), exponential megaphone, pre-chamber, chamber and air release hole.

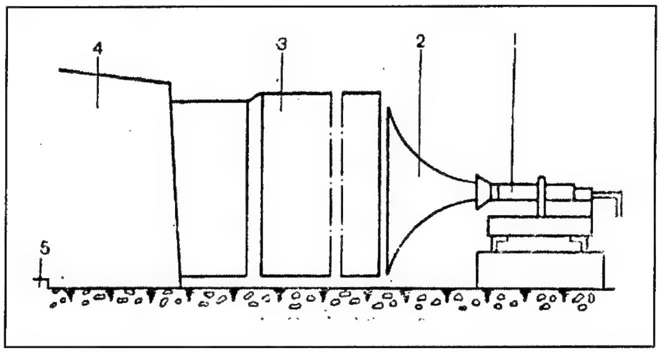


Figure 2.9 - R. Rocache testing chamber (1971)
1 - pneumatic generators; 2 - exponential megaphone; 3 - pre-chamber; 4 - testing chamber; 5 - air outflow hole

The chamber volume is 20 m^3 and exponential megaphone volume is 2 m^3. Useful volume is 22 m^3. The generator is of siren type (rotated disks with holes). The maximum rotation rate is 3,500 rpm. Generator is electronically controlled. Maximum sound pressure levels were obtained in the wave guide (170 dB), exponential megaphone (166 dB) and chamber (160 dB). The exited spectrum is of wide band character from 40 Hz to 40 kHz.

D.L. Johnson (1974) has dynamic vacuum chamber which had sound pressure levels of up to 144 dB. To get higher levels (172 dB) at 8 Hz two additional pumps were used.

H.G. Leventhall (1974) has used chamber of 1×1.2×1.8 m sizes (see scheme in Figure 2.10). At the frequency band of 2 to 20 Hz white (continuos) spectrum can be reproduced with total sound level pressure of 126 dB. Tonal signals have reached 145 dB. The same chamber was used by N. Yeowart (1974).

Figure 2.11 demonstrates P. Borredon, J. Nathie (1974) installation to evaluate infrasound health effects in humans.

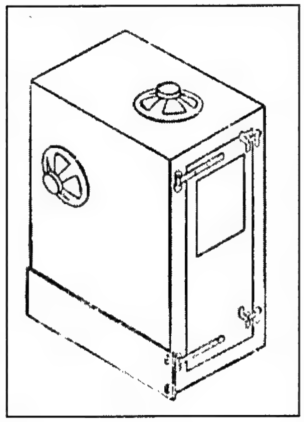


Figure 2.10 - General view of experimental chamber (Leventhall H.G., 1974)

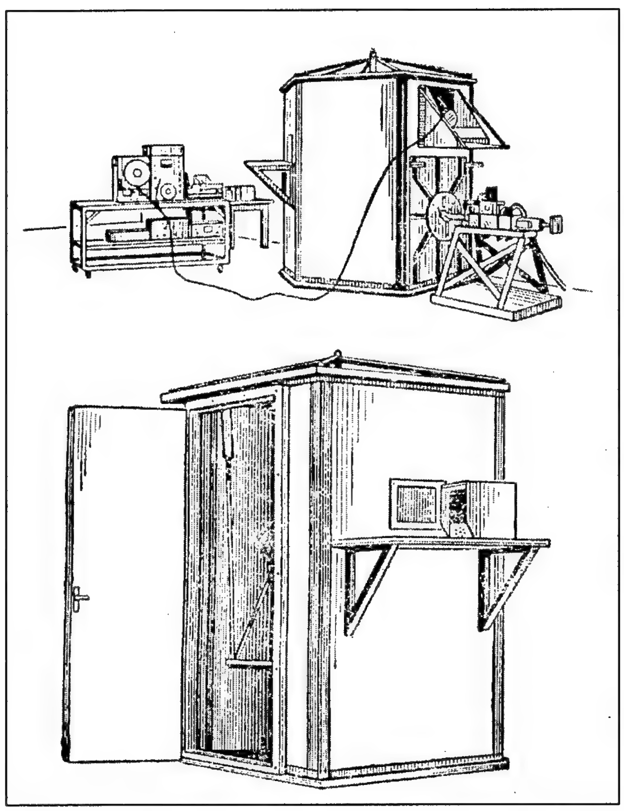


Figure 2.11 - Testing chamber (Borredon P., Nathie J., 1974)

The sound pressure level is 130 dB at 7 Hz frequency. To assess infrasound effects in the hearing organ (Evans M.J., 1972; Leventhall H.G., 1974; Izmerov N.F. et al, 1998) special electrodynamic earphones were used (Figure 2.12).

N.F. Izmerov et al (1998) have used ear couplings. However, this aural generation method is inadequate to real exposure conditions.

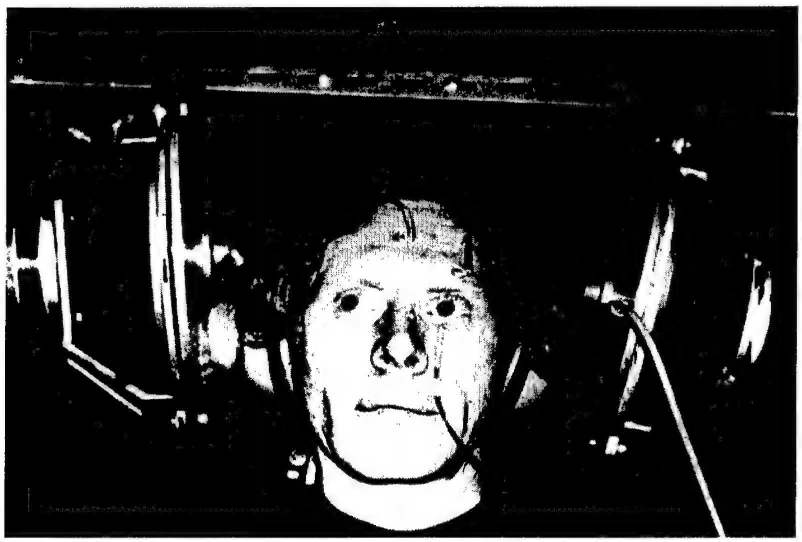


Figure 2.12 - Aural method of infrasound generation

2.2 General technical principles of generating equipment applied by Russian researchers to examine health effects of the infrasound and low frequency oscillations

The obvious advantages of the infrasound laboratory simulation done by dynamic pressure chambers (DPC) include widely varying parameters, experiment elaboration effectiveness, and relative simplicity of the technical realization.

According to the excitation principle DPC are subdivided into three types as follows:

- electromechanical;
- electrodynamic; and
- pneumatic.

According to the varying pressure creation technique, chambers can be subdivided into the following types:

- varying volume;

- constant volume; and
- resonance volume.

The varying volume DPC the pressure is changed via chamber volume change. This can be realized by moving piston or elastic membrane.

Piston constructions are most common (electromechanical excitation principle), which is specific to less contortions of the chamber pressure law.

Membrane constructions (electrodynamic excitation principle) is less common for DPC because of the absence of reliable membrane constructions.

Constant volume DPC (pneumatic excitation principle) has the advantage of moving drive parts resulting to higher frequencies.

For all DPC types it is necessary to provide reliable potting and sound isolation because the noise level (at 130 dB levels, essentially) of the drive and other components can be of the same order.

The first Russian dynamic pressure chamber has been developed in Leningrad Sanitary and Hygiene Institute (Karpova N., Malyshev E., 1981). The chamber size (2 m^3) is determined by 1 h physiological tests.

Low frequency oscillation generation is done by special appliance which simplified scheme is given by Figure 2.13 where (1) is elastic membrane of 60 cm diameter, (2) is diffuser covered by vibration damping material (3). Duralumin discs (4) are in the membrane center. Driving mechanism (5) is equipped with stabilizer (6) to attenuate parasitic oscillations. The flywheel (7) is fixed on the arbor of electric motor (8) placed on the table (9). The mechanical part is covered by sound isolation corps (10) having outflow channel (11). The diffuser is connected to the low frequency filter (12) by flexible fixings (13) not to pass the noise in the chamber (14) having pressure compensatory system (15) and loudspeakers (16).

This complex produces sinusoidal oscillations of 1 to 20 Hz with sound pressure levels of 90 to 150 dB.

In small volume chamber (30 l), maximum infrasound levels were 170 dB. The resonance frequency is 12.5 Hz and the generator sound power is 560 W.

In 1976-80 the Institute of Biophysics has developed a number of generators to make volunteer tests and animal experiments.

These systems have included dynamic pressure chambers and free air oscillation generators which were more preferable for biological studies because of the generating of variable pressure and oscillation velocity together.

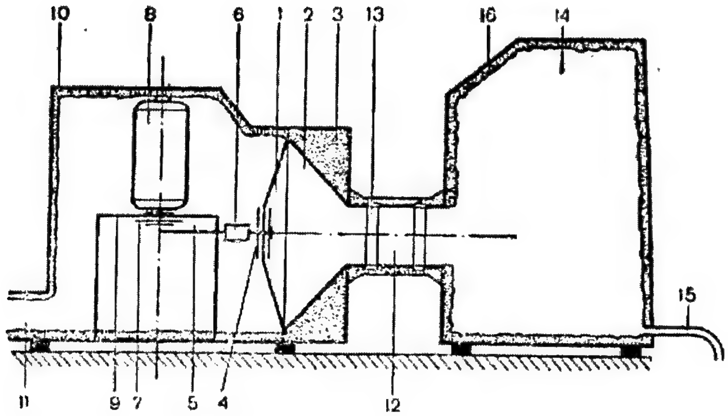


Figure 2.13 - Principal scheme of experimental infrasound complex for biological studies (Karpova N., Malyshev E., 1981)
(see text explanation)

2.2.1 Dynamic pressure chambers to examine health effects of the infrasound and low frequency oscillations

Stationary chamber of dynamic pressure (DPC-1)

The chamber has constant volume and electromechanical excitation (see Figure 2.14).

The generator creates infrasound air oscillations of 1-20 Hz inside the chamber (Figure 2.15). To decrease noise level most noisy equipment (electric motor and hydropump) are placed outside the working premise which has decreased the room noise from 85 to 77 dB.

Technical specification of DPC-1:

- inner volume	2.5 m^3;
- dynamic range	100-175 dB;
- frequency band	1-12 Hz;
- weight	10000 kg;
- generator drive power	75 kW.

DPC-1 peculiarities are as follows:
- step-changeable sound pressure level inside the chamber;
- almost sinusoidal change of the chamber pressure;
- human and animal experiments are possible;
- gradual frequency change with single sound pressure level.

Figure 2.14 - Stationary chamber of dynamic pressure (DPC-1)

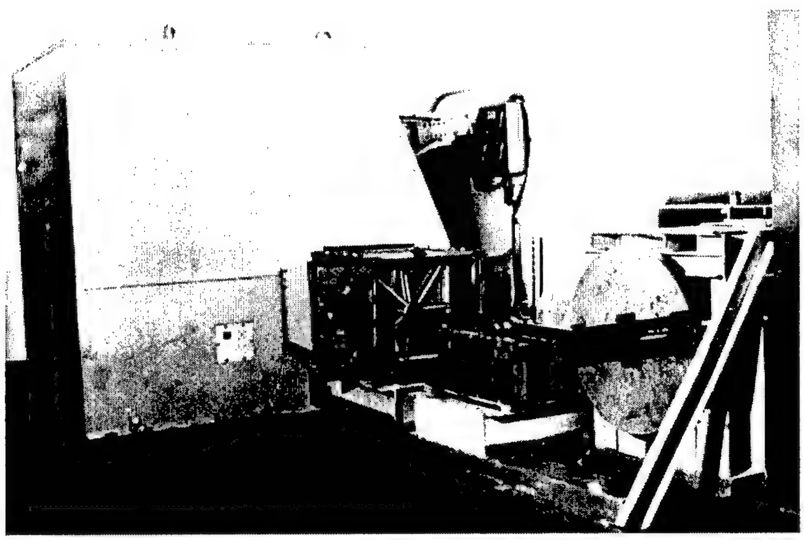


Figure 2.15 - DPC-1 chamber generator

Pneumatic chamber (DPC-2)

The installation is the constant volume chamber with pneumatic excitation of oscillations (Figure 2.16-2.17).

Technical specification:

- frequency band	0-50 Hz
- pressure in buffer chamber	1.1 and 0.9 atm
- test chamber volume	0.025 m^3
- maximum noise level at 1 m	72 dB
- consumed power	500 W
- sizes	1×1×0.75 m
- weight	200 kg

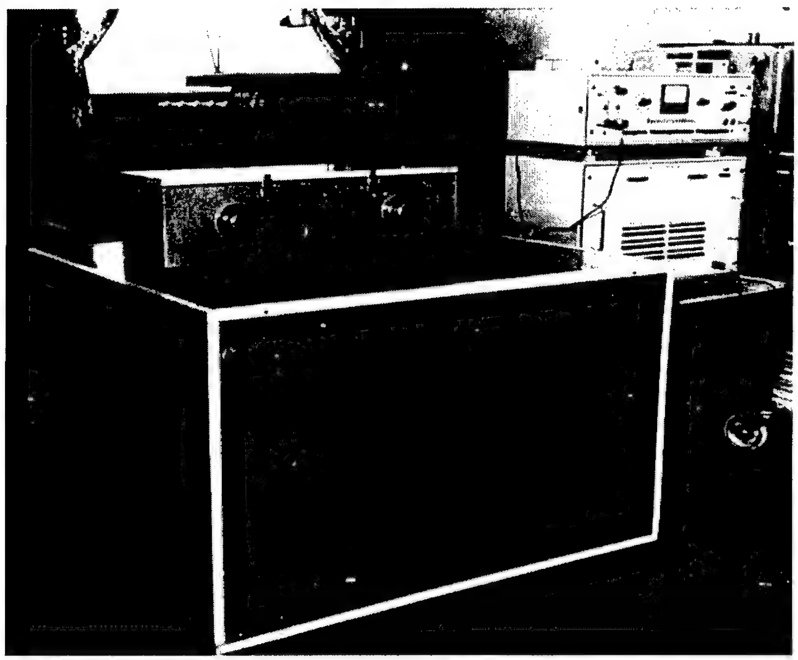


Figure 2.16 - DPC-2 general view

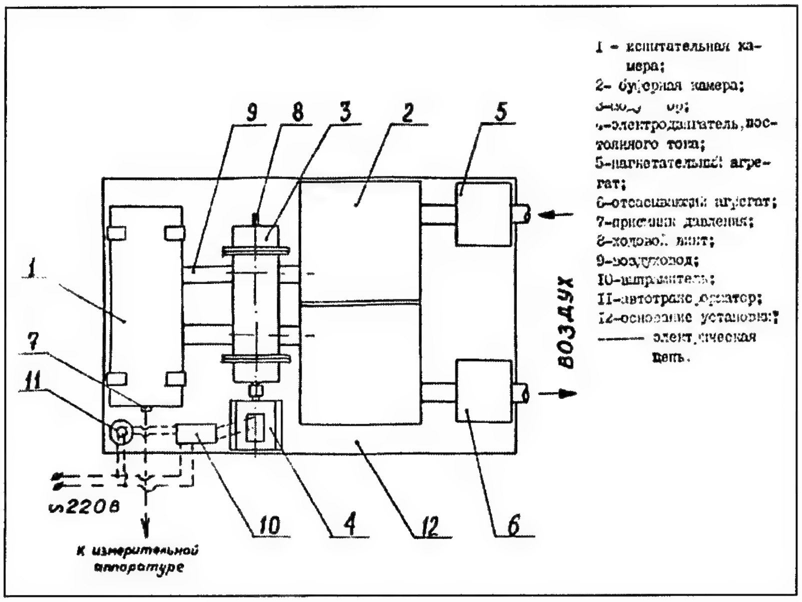


Figure 2.17 - DPC-2 scheme

Figure 2.18 provides AFC in test chamber with open passage cross-sections of the modulator.

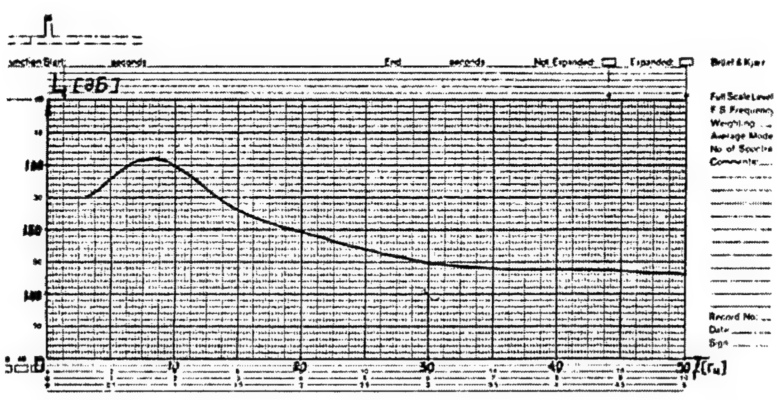


Figure 2.18 - AFC of testing chamber

The pressure change curve at 7 Hz is shown by Figure 2.19, and its spectrum is shown by Figure 2.20.

Other peculiarities of the installation:

- the absence of vibration;
- wide frequency band;
- high pressure levels in the test chamber;
- dangerous noises are absent outside the chamber;
- variable working frequency;
- unlimited operation time if proper cooling is provided.

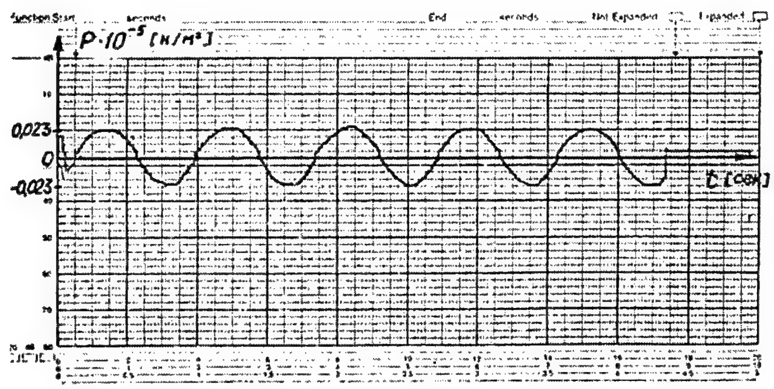


Figure 2.19 - Pressure change law

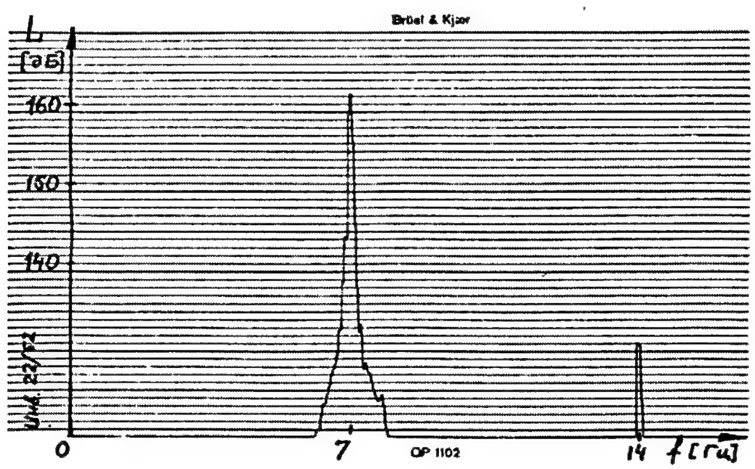


Figure 2.20 - DPC-2 spectrum

Electrodynamic chamber (DPC-3)

The general view is shown by Figure 2.21.
Installation components:
- dynamic pressure chamber;
- control shield;
- electrodynamic vibration test unit;
- power amplifier;
- magnetizing power supply;
- control system;
- measuring equipment.

DPC-3 specifications:

- frequency band	from 5 to 50 Hz
- maximal amplitude of the chamber pressure	up to 160 dB related to $2\cdot10^5$ Pa
- chamber volume	0.07 m^3

Table 2.1 Amplitude-frequency characteristic (AFC) of DPC-3

Frequency, Hz	5	10	15	20	25	30	35	40	45	50
Pressure, dB	154	155	155	155	155	155	155	155	155	155

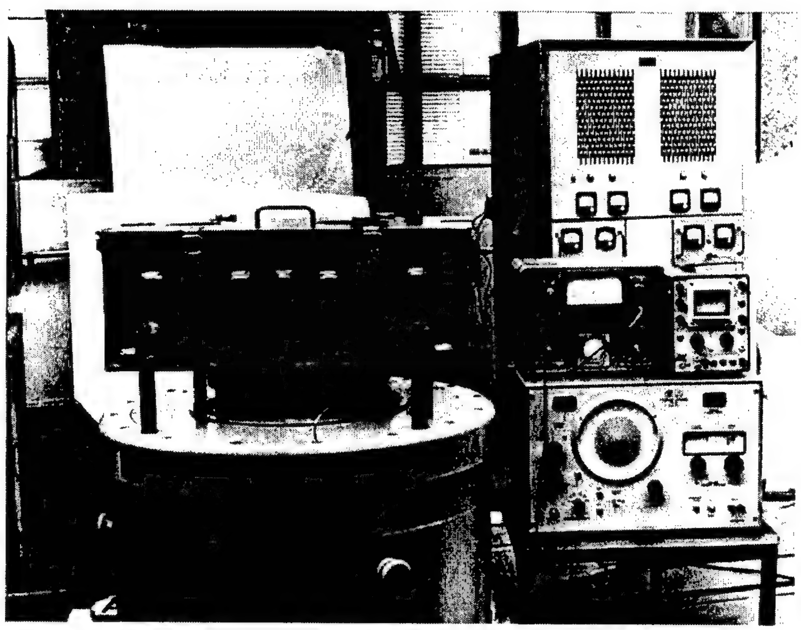


Figure 2.21 - DPC-3 general view

Small piston acoustic testing chamber (MAIK)

In 1980 first considerations of such installations have arisen which was realized the preliminary installation with short wave guide and ten speakers (10 W power each). The frequency band was 0.5 to 50 Hz. The experimental sound pressure was 130 dB which could be elevated to 140 dB due to resonance phenomena.

Small acoustic testing chamber (MAIK) was the next step (see schemes of Figure 2.22-2.23). The working frequency band is 2 to 25 Hz; maximal sound pressure level is 150 dB.

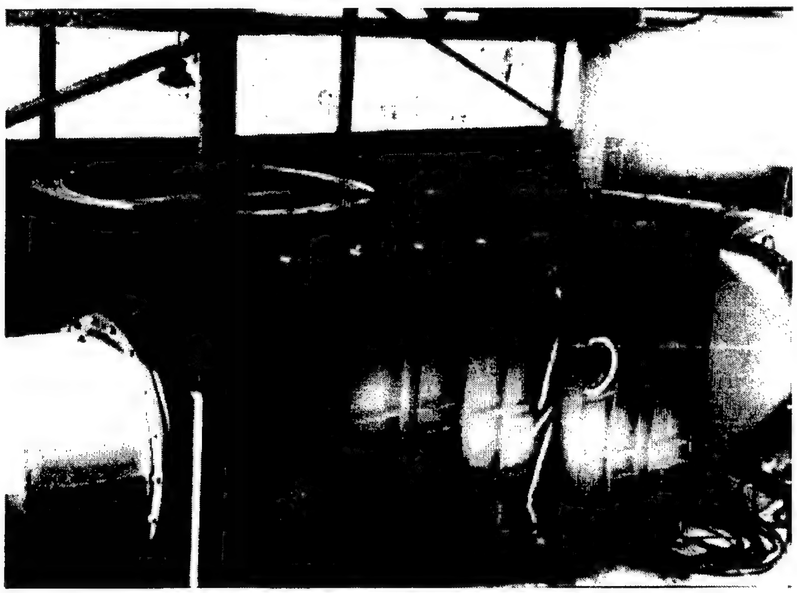


Figure 2.22 - "MAIK" acoustic testing chamber

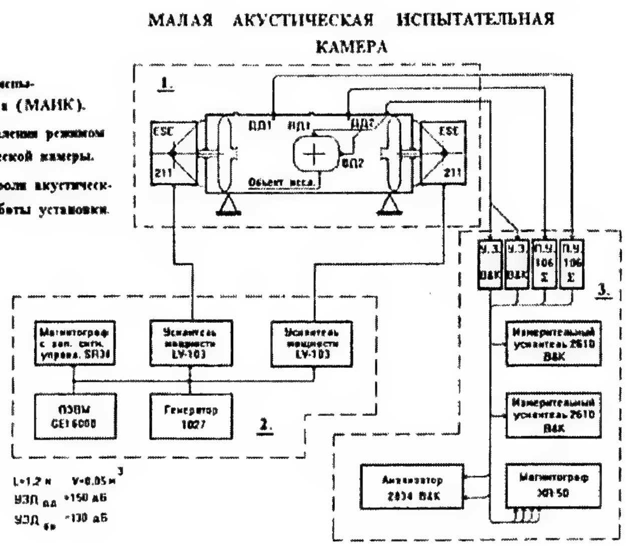


Figure 2.23 - Box diagram of testing chamber

2.2.2 General technical principles of low frequency generators with free propagation of acoustic oscillations

Theoretical calculations and previous experiments indicate to the fact that the far field of the infrasound emitter is the distance of the wavelength of the wave emitted.

Currently, high power infrasound generators (50 kW) are created including thermoacoustic generators, piston generators and gas flux generators (whistles).

Thermoacoustic generator - 1

The generator created in 1976 by the Institute of Biophysics is able to transform the continous heat flow into acoustic oscillations.

General view and installation scheme is shown by Figures 2.24-2.25.

The cooling of the glass pack is done by water and the frequency change is provided by helium inflow in the resonator which results to frequency change from 8.2 to 20 Hz, whereas the sound pressure level increases from 109 to 126 dB.

Technical specifications:

- sizes	11×2×1 m
- aperture diameter	0.3 m
- frequency	8.2-20 Hz

- maximum sound level
  - a) at 8.2 Hz 109 dB
  - b) at 20 Hz (He inflow) 126 dB

Figure 2.24 - General view of thermoacoustic generator

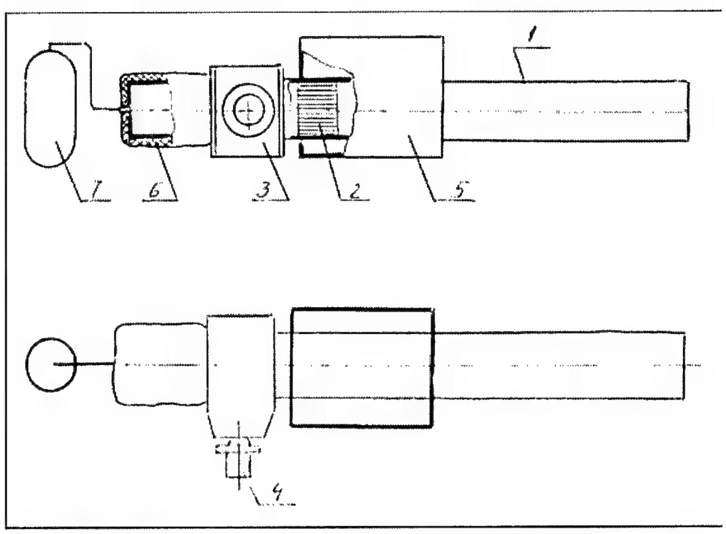


Figure 2.25 - Thermoacoustic generator scheme:
1 - resonator; 2 - glass pipe pack; 3 heating device; 4 - burner;
5 cooling fluid reservoir; 6 thermoisolation layer; 7 helium cylinder

"Orpheus" thermoacoustic generators

Acoustics Institute generators (Orpheus-1 and Orpheus-2) have optimal frequency of 18.7 Hz. Frequency band is 20.5 to 16,5 Hz. Work time is 10 min. The free air sound pressure level is 140 dB (Figure 2.26).

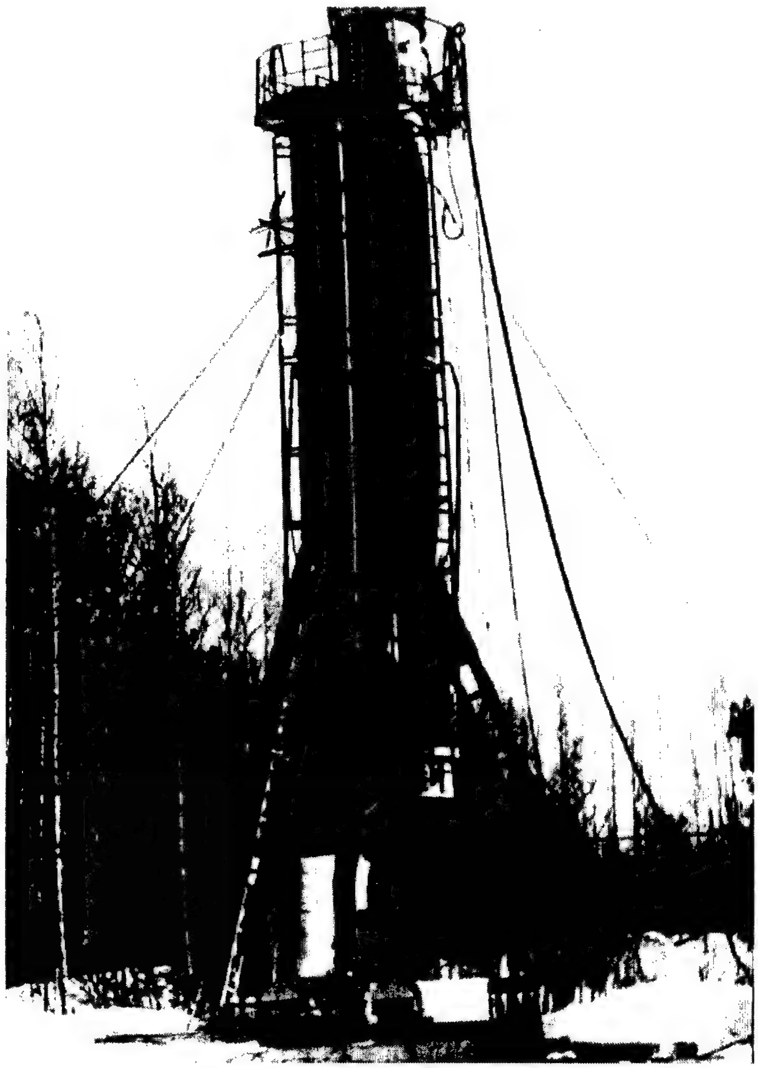


Figure 2.26 - "Orpheus" thermoacoustic infrasound emitters

Resonance emitter "Alpha"

The pneumatic siren was modified to increase the infrasound emission using quarter-wave acoustic resonator.

The energy portion at basic frequency is 60-70% at the borderline of the "far field" and reaches 98% at five wavelength distance.

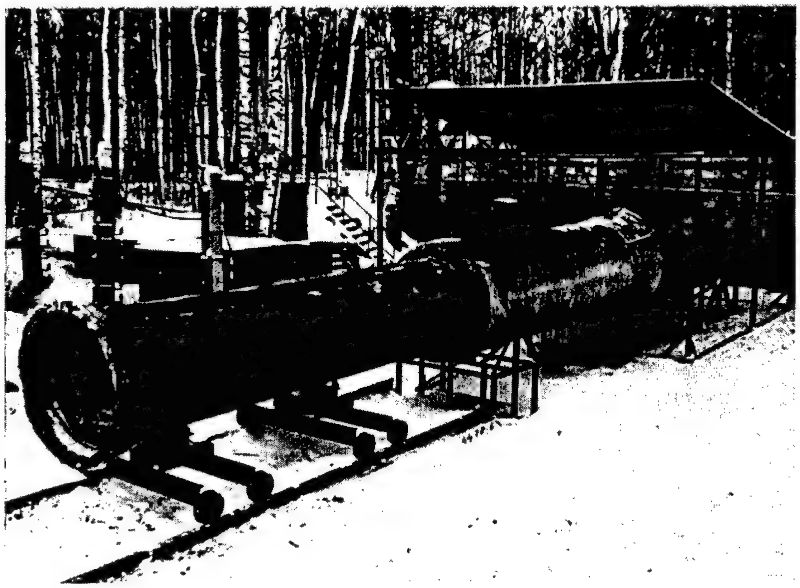


Figure 2.27 - "Alpha" installation: general view

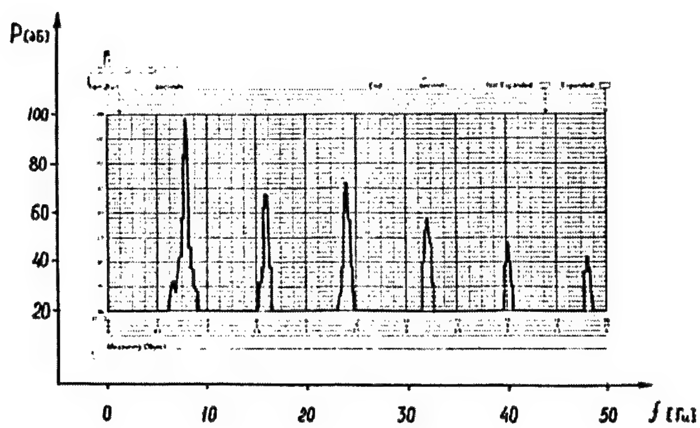


Figure 2.28 - "Alpha" installation: emission spectrum

Acoustic power depends on frequency and is equal to 100 W to 20 kW in 4-45 Hz frequency band. At 3-5 wavelength distance the difference between total sound pressure level and basic frequency sound pressure level is less than 2 dB. The duration of work at maximal power is 50 s.

Pulse combustion chamber ("Alpha-1")

Modifications of Alpha installation include pulsing combustion chamber and gas guide of changeable length depending on the emission frequency.

The modification has resulted to power increase for 50-60% (6-15 kW at 7-15 Hz). Maximal power work time was increased to 180 s.

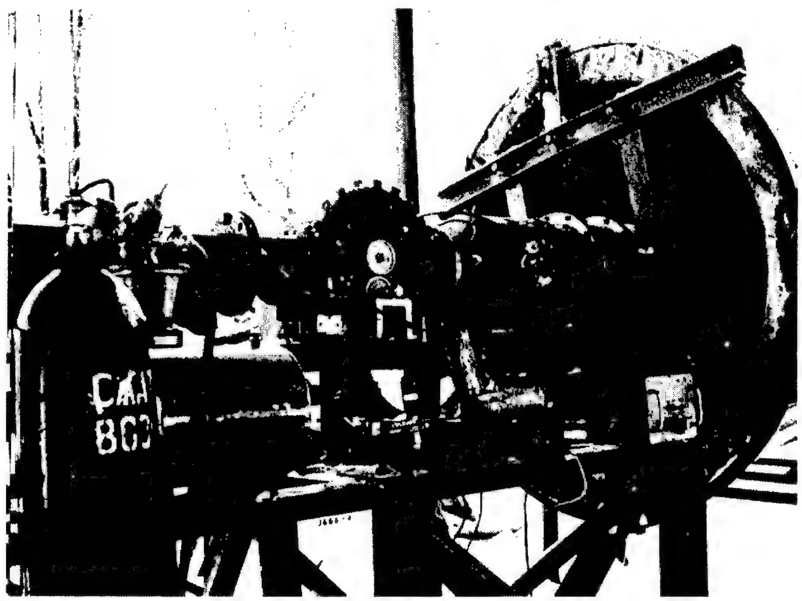


Figure 2.29 - Pulse combustion chamber

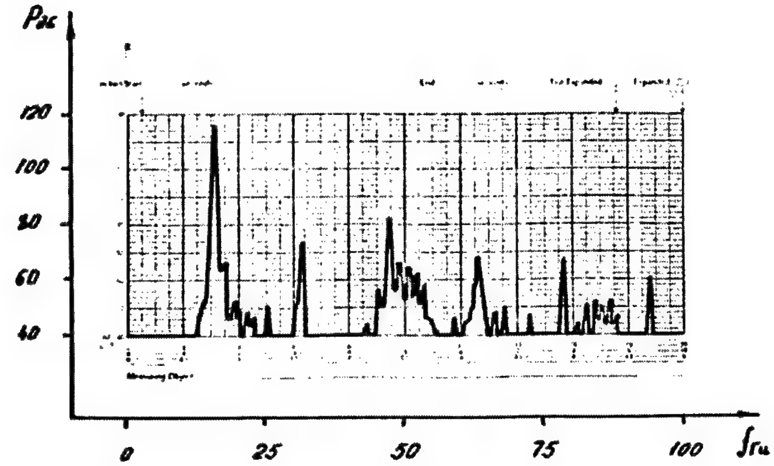


Figure 2.30 - Emission spectrum of "Alpha-1" installation: combustion mode

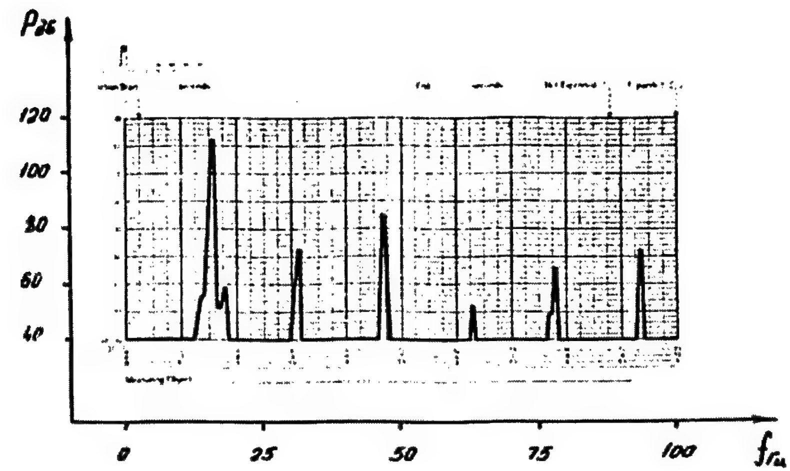


Figure 2.31 - Emission spectrum of "Alpha-1" installation: resonance mode

Membrane resonance emitter ("Resonator")

Piston excitation provides the relatively monochrome emission and proper sizes of the emitting equipment.

The calculated dependence of sound pressure amplitude versus distance to generator (curve 1) and that measured practically (curve 2) are shown by Figure 2.32.

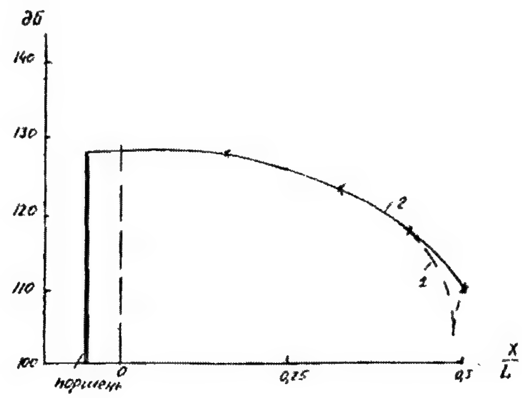


Figure 2.32 - LSP distribution inside resonator
(X - distance from the resonator center; L - resonator length)

If the pressure level at generator outlet is L=110 dB, the energy intensity level is 107 dB.

Maximal drive power (18 kW) can provide the energy intensity level of 120 dB with pressure level of 135 dB.

The installation consists of:

- resonator;
- excitation system;
- control system;
- parameter monitoring system.

Resonator is the concrete pipe (L=34 m) with rectangular cross-section of 2,5×2 m^2 (Figure 2.33-2.34).

Acoustic parameters of the generator: 4.8 Hz emission frequency (varies from 4 to 10 Hz); 1^{st} acoustic resonance frequency is 4.8 Hz at 15^0C air temperature. Maximum sound pressure level is 120 dB at 4.8 Hz.

Table 2.2 provides sound pressure levels at frequencies of $f_i = f_1 \cdot n$, where f_1 = 4.8 Hz; n is the harmonic number at the outlet of the generator.

Table 2.2 Pressure level values

Harmonic number	1	2	3	4	5	6	7	8
Frequency, Hz	4.8	9.6	14.4	19.2	24.0	28.8	33.6	38.4
Pressure levels, dB	114	108	112	110	96	96	102	98

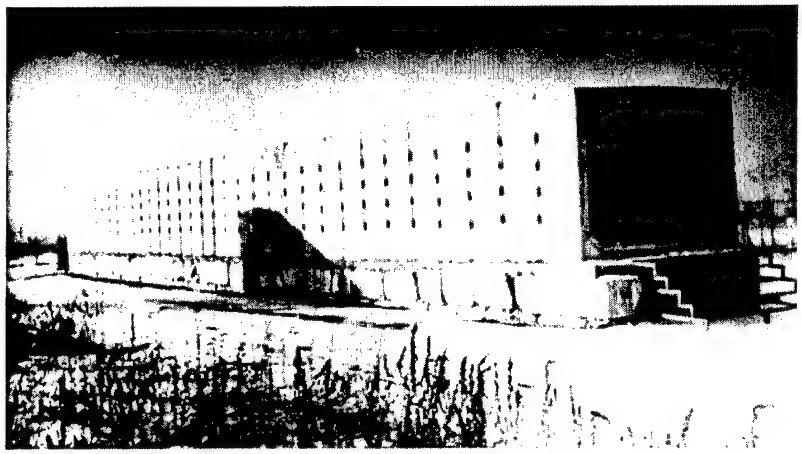


Figure 2.33 - Resonator: general view

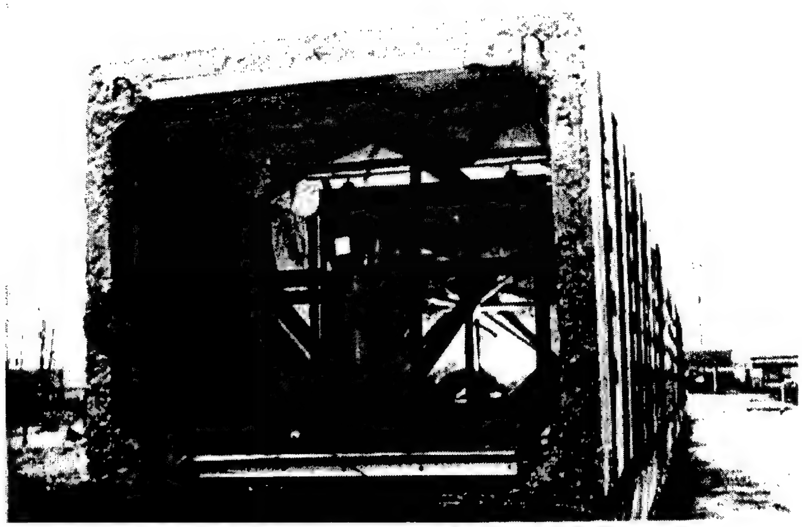


Figure 2.34 - Resonator view: drive side

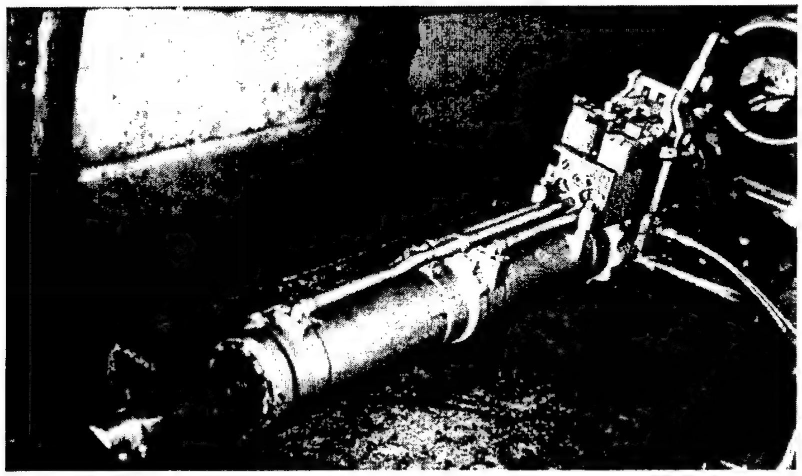


Figure 2.35 - Hydrodrive

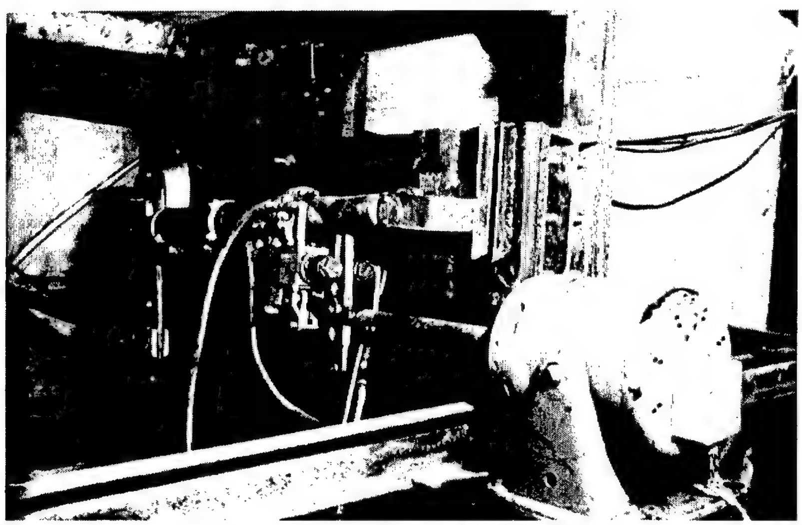


Figure 2.36 - Hydrodrive system; general view

Gas flux emitter ("Svistok")

General view of gas flux emitter is shown by photo (Figure 2.37).

Figure 2.37 - Infrasound gas flux emitter

The emitter (see scheme) consists of generator (1), nozzle (2) and resonator (3).

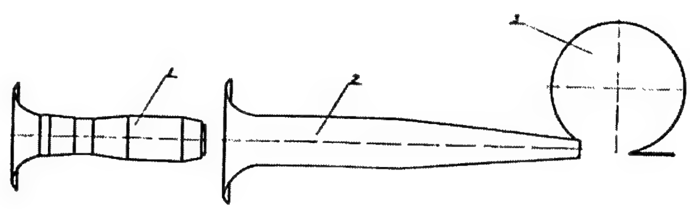


Figure 2.38 - Gas flux emitter scheme

The gas generator is the routine aviation turbojet engine with air supply tube, ignition and supply systems, and ejector.

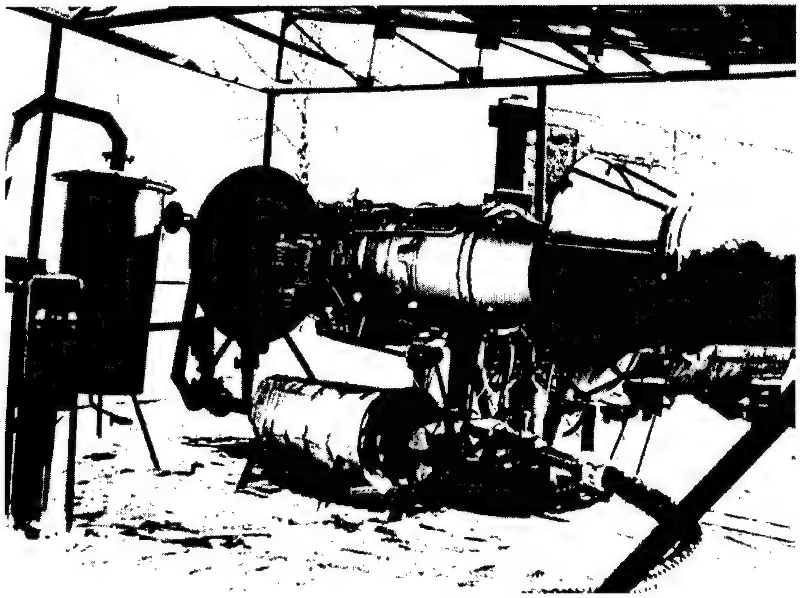


Figure 2.39 - Gas generator on the basis of the airplane engine

Engine specifications:

Engine type	AI-25, two contours, turbojet, two rotors
Fuel	TS-1 aviation fuel
Fuel flux rate kg/h:	
Take-off mode	855
Nominal mode	632
0.4 nominal mode	301
Time of continuous operation, min:	
Take-off mode	< 5
Middle power mode	< 30
Other modes	unlimited
Technical resource, h	500
Maximal permissible gas temperature beneath the turbine, ^{0}C, less than:	
Take-off mode	630
Start-up and middle power mode	600
Other modes	550
Engine weight, kg	< 350
Sizes, mm:	
length	1995
width	820
height	896

The engine is fixed on pillion at 1300 mm height. Air supply pipe provides continous inflow.

The ejector is presumed to eject air resulting to the generator productivity increase.

The nozzle provides gradual change of flux cross-section from round to rectangular one of 1500×230 mm sizes. The nozzle is connected to resonator.

The resonator is an armored concrete construction of 6000×6000×2000 sizes. Moving knife provides the changeable distance between nozzle and knife (from 2,000 to 2,650 mm).

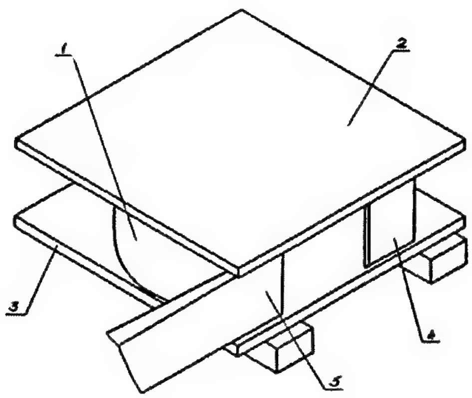


Figure 2.40 - Gas flux emitter resonator
1 - shell; 2 - upper cover; 3 - lower cover; 4 - moving knife

The gas flow emitter operation principle is as follows. The gas flux enters the ejector mixing chamber where gas flow is mixed with ejected gas. Than the flux is formed in the front part of the nozzle and "plain" flux (1500×235 mm) comes out of the nozzle. The outgoing gas flux comes to the edge of the resonator window, where it is divided into two parts. The part of the flux comes inside the resonator inducing acoustic oscillations. Small oscillations inside resonator also induce gas flux oscillations. The oscillating flux is periodically deviated inside and outside the resonator, so the reverse action pulses are induced in resonator. Thus, auto oscillating system of gas flux and resonator is created, which frequency is similar to that of resonator itself. The generator radiation is monochromatic and has very directional character. Emission spectrum at 75 m from resonator window is shown by Figure 2.41, and directional diagram is shown by Figure 2.42.

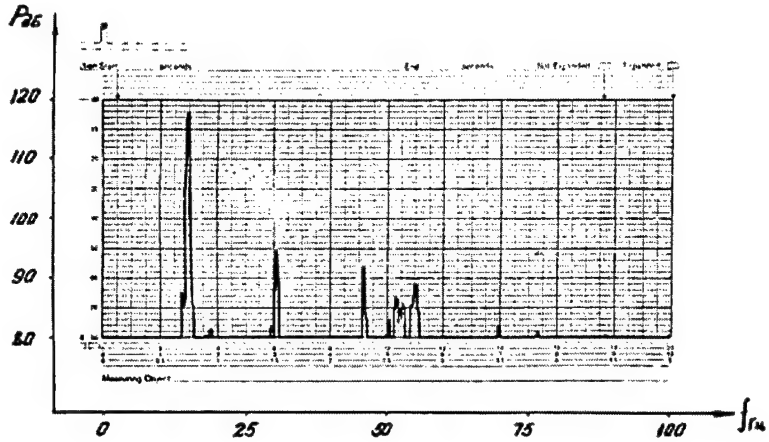


Figure 2.41 - Gas flux emitter: emission spectrum

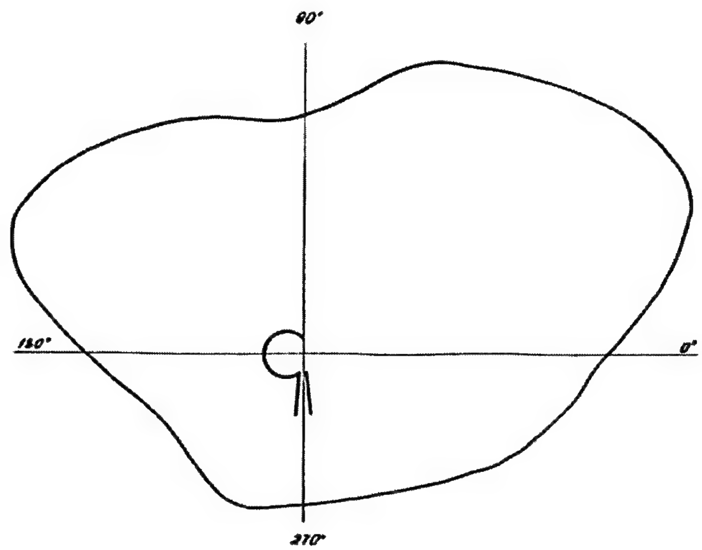


Figure 2.42 - Directional diagram of gas flux emitter

The radiation concentration coefficient is equal to two, which provides sound pressure of point source power of 50 kW. The work time is limited by the volume of the fuel tank.

Gas flux emitter specification:

Emission frequency, Hz	12–15
Maximal power, kW	25
Concentration coefficient in the maximum emission direction	2
Work time, min:	
25 kW	< 5
15 kW	180 (limited by the volume of the fuel tank)
Resonator sizes, m:	
Diameter	5.8
Height	2

Chapter 3 BIOLOGICAL EFFECTS OF LOW FREQUENCY ACOUSTIC OSCILLATIONS (SURVEY OF EXPERIMENTAL AND PHYSIOLOGICAL HYGIENIC STUDIES)

The literature data regarding industrial infrasound effects in human and animals are limited for the initial phase of studies development. Systematic studies devoted to low frequency acoustic effects were started in 1970th - 1980th. These studies have indicated to the fact that 110 dB to 174 dB infrasound is able to induce unpleasant subjective reactions: nausea, chest vibration, stomach pains, headaches, giddiness, unexplained fear, swallowing and breath complications, spatial disorientation, tympanic oscillation and tympanic massage sensation (Andreeva-Galanina E. Tc., 1970; Karpova N.I. et al, 1973; Reutov O.V., 1978; Evdokimova I.B., Shypack E.Yu., 1979; Gavreau V., 1966; Pimonow L., 1976; Gierke H.E. von, Parker D.E., 1976; Tempest W., 1976).

Table 3.1 - Infrasound exposure symptoms ("Physical factors manual", vol. 2, Moscow, 1999)

Symptoms	Publication number (see footnote)																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Giddiness		+	+	+	+	+		+	+	+		+	+	+			+	+
Nausea		+	+	+	+	+		+	+	+		+	+					+
General fatigue, adynamia		+	+	+	+	+			+	+	+		+	+		+	+	
Chest and internal organ vibration sensation		+	+		+	+				+	+		+					
Headache	+	+	+	+	+					+		+	+	+	+	+		
Paling or redness of skin			+		+							+	+					
Swearing		+	+									+	+					
Salivation													+					+
Mouth dryness		+	+		+					+						+		
Mental disturbances (fear, spatial disorientation, intellectual contusion)			+		+	+	+	+	+		+		+			+		
Vision disturbance (fogginess)		+	+		+	+				+		+				+		
Breath complication and/or breath rate change		+			+				+	+	+		+					+
Strangulation					+	+				+						+		
Caught				+						+			+					
Voice modulation					+	+				+								
Swallowing pain, obstructed swallowing			+		+	+				+			+					

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Chest pressure sensation					+								+					
Vomiting attacks, vomiting			+		+	+						+	+					
GIT disorders (eructation, lost appetite, meteorism etc.)			+		+	+			+		+	+	+					
heartache, palpitation					+				+		+							+
Static kinetic disturbances					+	+			+		+							
Sensitivity decrease											+							
Prostration (in some cases)									+		+							
Sleepiness		+	+		+	+						+	+					
Insomnia				+													+	
Fever-like tremor	+				+	+												
Sea sickness disease												+	+					
False unreal feelings					+	+												
Palate and facial skin stiffness					+	+												+

Footnote: 1. Andreeva-Galanina E. Tc., 1970; 2. Reutov A.N., 1976; 3. Karpova N.I., Malyshev E.N, 1981; 4. ; Shypack E.Yu., 1981; 5. Izmerov N.F., 1996; 6. Kuralesin N.A., 1997; 7. Mills G.A., 1934; 8. Wever E.C., Bray C.W., 1936; 9. Mohr G.C., Cole J.N., Guild E., Gierke H.E. von, 1965; 10. Alford B.R. et al., 1966; 11. Gavreau V.R., 1965; 12. Quercy I.V., 1966; 13. Grognot P., 1969; 14. Nathie J. et al., 1969; 15. Whittle L.S. et al., 1972; 16. Cabal C., Roszak E., 1974; 17. Prazak B., 1974; 18. Broner N., 1978.

Early published infrasound health effects in human are described by Table 3.2.

Table 3.2 - Infrasound human health effects

Author(s)	Sound pressure level, frequency, exposure time	Health effects
Slarve R.N., Johnson D.,1975	144 dB; 1-20 Hz; 6 min	Audiometry has not revealed significant shifts for aural analyzer in males
Borredon P., Nathi L., 1974	130 dB; 7,5 Hz; 50 min	Some increase of diastolic pressure in males from 61.9 to 63.2 mm
Karpova N.I. et al 1972	136 dB; 10 Hz; 15 min	Pulse rate increase and minimal AD increase (for 7-11 mm) in males
Reutov O.V., Erofeev N.P., 1976	135 dB; 5 _ 10 Hz; 15 min	Heart automatism disorder with peculiar change of cardiac constrictions
Gierke H., 1974	154 dB; 1-100 Hz;	Unpleasant sensations in the ear have risen from 145 dB; 150-153 dB was the limit threshold of voluntary tolerance. At these levels, the scratching sensation and outside body presence sensation have occurred in the throat; caught attacks have started and some males had nausea feeling.
Nixon Ch., 1974	> 125 dB; 1-20 Hz; 8 min	125 dB and more results to tympanic massage coinciding to the oscillation frequency. > 140 dB has induced pain sensation. At 10 Hz, the pain threshold was ~ 150 dB. The pain threshold is increased for the decreasing frequency.
Karpova N.I. et al 1972	136 dB; 10 Hz	Significant change of the peripheral blood circulation (20-22% blood flow increase if compared to initial data)

Evans M., Tempest W., 1972	140 dB; 7 Hz	7 Hz frequency is most "effective" for vestibular apparatus; this frequency is sensible for semicircle channels and otolith system detecting the gravity
Prazak B., 1974	80-152 dB; 4 Hz	At 4 Hz the tolerance threshold is 87 dB and pain threshold is ~152 dB.
Sherer, J., 1973	140-170 dB; 3, 15 and 100 Hz;	The pain threshold was found to be as follows: 170 dB for static pressure; 165 dB at 3 Hz; 140 dB at 15 Hz and 120 dB at 100 Hz
Leventhall H., 1974	126 dB; 2 - 20 Hz	Subjective reaction studies in 6 volunteers have indicated to the average reaction time change from 0.414 s to 0.430 s in case of the infrasound exposure only. The "arrow surveillance" test was found to get 10% productivity loss in case of the noise or alcohol
Mohr Get al, 1965	119 - 144 dB; <22 Hz; 3 min	Subjective body vibration. At 144 dB, half of examinees had breath rate increase. All examinees had transient shift of the aural threshold (>120 dB)
Alford B. Et al, 1966	Up to 154 dB; 1 - 100 Hz	150 dB is tolerable for heart rhythm, aural threshold, vision power, spatial orientation changes
Gavreau V., 1968	7 Hz	Low intensive 7 Hz infrasound induces nausea and fatigue at hour 2 of the exposure of intellectual operator.
Sharp M., 1971	Low frequency noise during spaceship launch	Low frequency noise and vibration result to discomfort, irritation, nausea, abdominal and vertebral pains, obstructed breath and other unpleasant sensations, which pre-cause anxiety and fear
Johnson D., 1974	< 144 dB; 1 - 30 Hz	Voice modulation and middle ear pressure sensation in case of > 132 dB
Leventhall H., 1974	140 dB; 2 Hz	Mild nausea, rotation sensation, eyeball rotation, discomfort in all experiments
Fecci R. Et al, 1971	65-80 dB; 8 Hz; industrial exposure within 4 months	Arterial pressure indices were very stable within 4 months. Only 18% had mild AP decrease and 22% had mild AP increase. Pulse rate was stable. ECG changes were not found.
Malyshev E.N., Skorodumov G.E., 1974	135 dB; 10 Hz; 15 min	Cardiovascular status examination has revealed pulse rate increase (5-30 min^{-1}), minimal AP increase (20 mm) and maximal AP increase (15 mm) in males.
Pimonow L., 1976	-	10 year material generalization has suggested to the infrasound pressure limit of 140 dB for space fliers and 120 dB for space flight technical personnel
Johnson D., 1974	144 dB and more; 1 - 30 Hz;	160 dB is considered to be maximum permissible even for short-time exposure

The infrasound induces tympanic hyperthermia, which can be observed both at the time of exposure and thereafter (Nixon C., Johnson D., 1973). This hyperthermia can vary from mild to severe grade; the severe hyperthermia can be in the whole hammer handle. Detailed infrasound influence consideration for 100-140 dB was elaborated for aural analyzer taking into account effects of harmonics generated in case if intensive infrasound exposure. Some examined individuals have not been found aural changes whereas others have been detected to develop temporary shift of aural sensitivity threshold. The aural analyzer sensitivity to the infrasound exposure is generally similar to that for higher frequency noise, if the temporal aural threshold shift (TATS) is considered. The infrasound TATS variability is similar to that for sound frequencies.

In case of infrasound levels above 172 dB, D. Johnson (1974) has observed tympanic perforation and middle ear muscle hyperemia in

animals; however, the animals have not manifested anxiety. The author indicates that he has exposed himself to this infrasound for 30 seconds and found that painful sensations are absent but tympanic mechanical massage sensation is present. In case of the whole body exposure to 144 dB infrasound, the exposed persons were found to have voice modulation; the increase of middle ear pressure was noted for > 132 dB.

The peculiarity of industrial infrasound exposure consists in the "pure" infrasound absence; usually it is combined to low frequency aural noises. V.I. Palgov and N.N. Doroshenko (1975) have examined aural abilities in compressor operators exposed to infrasound (113 dB) combined to stable noise (85 dB). The comparison group was composed of mechanical workshop workers exposed to <90 dB without recorded infrasound exposure. It was established that the percentage of people with occupational bradyacuasia (grades III–IV) is 11.2% against 2.5% in mechanical workers. The aural function peculiarity of combined infrasound and noise exposure of compressor operators was the increase of aural thresholds at low and high frequencies, which certifies to the involvement of both basal and apical parts of the cochlea.

The industrial infrasound study has not revealed specific effects (Mozhukhina N.A., 1979). However, the examination of the functional state of compressor operators within work day dynamics has revealed the aural threshold increase at 125, 250, 500, 2000, and 3000 Hz, for < 5 dB in average. Besides, some decrease of hand persistence, diastolic arterial pressure increase, and ECG R–R interval decrease was found. When comparing stability diagrams, the moderate (< 40%) increase of the shift area of the gravity center projection was noted which indicates to the equilibrium system change. It was judged that industrial infrasound combined to wide band noise has not more significantly affected in aural analyzer and cardiovascular system, if compared to that of the wide band noise only.

The infrasound exposure is accompanied by the cerebral hemodynamics depression expressed by the venous outflow complication in skull cavity, which phenomenon has occurred at ~ 7–10 minutes of the infrasound exposure (Karpova N.I. et al, 1979). 135 dB infrasound at 10 Hz has evoked larger increase of rheography wave amplitude, its anacrotic phase extension and the tonic tension index decrease, if compared to that at 5 Hz.

When considering the issue of the harmful infrasound effect in aural analyzer, the harmful vestibular effect has to be considered. Studies elaborated by N.S. Yowart (1974) have to be discussed in this context. When doing monoaural infrasound stimulation, the expressed vertical nystagmus was noted in 85% of cases. The sound pressure level applied was in the range of 130 dB to 146 dB and frequency range was 2 Hz to 10 Hz. These data have given the opportunity to suggest that infrasound affects vestibular apparatus;

the most effective frequency was found to be ~ 7 Hz, which corresponds the sensitivity range of vestibular channels. The vertical nystagmus induced by infrasound indicates to the effect in otolith system.

The infrasound oscillations affect the supreme nervous activity. Experiments to compare infrasound versus alcohol were tried (Kyriakides K., Leventhall H.G., 1977). These studies have demonstrated that 2 Hz to 15 Hz infrasound of 110-120 dB levels has negatively affected the ability to fulfill simple tests; the equilibrium support, reaction time and surveillance function were also worsen. The workability analysis has demonstrated that both infrasound and alcohol has induced 10% worsening of basic task execution ability.

Experimental studies (Reutov O.N., 1978) devoted to infrasound (5 Hz and 10 Hz, 135 dB to 100 dB, 15 minutes exposure) have revealed that largest percentage of complains was composed of subjective sensations of general fatigue, weakness, depression, disseminated attention, sleepiness, heavy head, and ear pressure (in 100% of cases). Large number of complainers has indicated to breath obstruction, chest and abdominal wall vibration. The decrease of the breath rate, cardiac outflow amplitude decrease, perception speed decrease, increase of latent period of visual-motor reaction (for 14-8% in case of 135 dB and for 5-6% in case of 100 dB) were objectively noted.

The respiratory function and cardiovascular system are soundly affected by the infrasound. Animal experiments (dogs, monkeys) have demonstrated that 166 dB infrasound exposure has significantly decreased the breath rate and the breath was stopped in case of 172 dB infrasound exposure. The total exposure time was 14 hours (Johnson D., 1974). In case of 190 dB infrasound exposure within 7-20 minutes the expansion of blood vessels width and lung hemorrhages were found (macroscopic and microscopic examinations), which has concluded to serious infrasound effects in the blood vessels in case of 180 dB level.

Examinations of 42 young males exposed to 7.5 Hz and 130 dB within 50 minutes have demonstrated the increase of minimal arterial pressure and pulse rate, whereas maximum values of these indices were unchanged. E.N. Malyshev and F.E. Skorodumov (1974), P. Borredon and J. Nathie (1974) have shown that 15 minutes infrasound exposure results to abnormal state of cardiovascular system. The pulse rate was increased for 5-30 min^{-1} depending upon the infrasound intensity; minimal arterial pressure was risen for 20 mm, maximal arterial pressure was risen for 15 mm, muscular tonus was decrease for 3-12%, and breath rate was increased for 4 min^{-1} and more.

The exposure to large infrasound levels was noted by the chest and abdominal wall oscillations and so-called thoracic abdominal effect (Sanova A.G., 1977; Karpova N.I. et al, 1979). Such

phenomena can be explained by the presence of acoustic impedance of these body parts (i.e. they are good infrasound conductors), so the major portion of the infrasound energy penetrates throughout the chest and abdominal wall.

The resonance frequency of the whole system of "abdominal cavity - chest" is in the range of 40-60 Hz in case of the volumetric infrasound exposure; at the same time, the chest resonance in case of single dimensional oscillations (human vibration experiment) is 4-8 Hz (Gierke H.E. von, 1974).

To get the objective examination of the infrasound health effects, H.E. von Gierke has made the model of human body to imitate acoustic impedance and to assess infrasound exposure intensity assessment to get the lung damage similar to that from the shock waves. These studies have demonstrated that belts application is inconvenient to suppress abdominal oscillations, because of more dangerous resonance oscillations at higher frequencies (10 Hz). It was concluded that high intensity infrasound is less harmful than correspondent levels of higher frequency sound or vibration.

The survey (Broner N., 1978) devoted to low frequency noise effects in human has considered infrasound (0-20 Hz) and low frequency noise (20-100 Hz) effects; it was noted that low frequency noise effect is more expressed than the infrasound one, though both effects are poorly investigated.

R.D. Gabovich et al (1979) have examined chronic infrasound of 8 Hz and 90, 115 and 135 dB intensities in case of animal exposure within 4 months (2 hours per day). This study has demonstrated that infrasound affects energy metabolism and body ultrastructure of rat myocardium. Changes of different intracellular structures (mitochondrias, endoplasmic reticulum, Holdgi apparatus) were already observed at 90 dB infrasound exposure. The resulting disturbance of routine enzymatic activities was found. In case of the exposure to 115-135 dB, the disturbances of the oxidative phosphoring processes, corticosterone increase in plasma, and catecholamine content decrease were noted, which is related to the long term stimulation of sympathetic adrenal system. Similar studies as well as studies elaborated by S.V. Alexeev and E.N. Kadyskina (1976), V.I. Vasiliev (1976), N.I. Karpova et al (1976), V.L. Ponomareva et al (1979) including some indices of albumin metabolism and microcirculation of soft cerebral cover vessels in white rats has given the opportunity to clarify intimate mechanisms of health effects induced by the infrasound exposure.

Thus, though the comprehensive investigation of LFAO health effects is still to be continued, it can be concluded that infrasound affects functional state of aural and vestibular analyzers, respiratory function, nervous and cardiovascular systems, which effects depend upon pressure level and frequency of the infrasound. The peculiar attention should be attracted to nervous emotional system,

workability and fatigue ability, when investigating infrasound effects in human for hygienic purposes.

Many researchers have described different infrasound reactions of cochlear vestibular apparatus. Recent volunteer studies (Kuralesin N.A., 1997) devoted to peculiarities of cochlear vestibular apparatus reaction has demonstrated the presence of alternative frequency-effect ratio of aural and vestibular sensitivity. The increase rate of vestibular related reactions was 2-2.8 times higher than that for aural ones. The sum of these two mechanisms was considered to be responsible for resultant spectrum of functional and pathological changes.

Basing upon data of N.F. Izmerov et al (1998), the vestibular analyzer receptors are considered to be adequate to the infrasound perception rather than aural ones. The specific peculiarity of nuclei vestibular complex is the unusually large development of outer ways connecting nuclei to different anatomical structures of the brain, especially to dorsal vagus nuclei. These connections provide global influence of the vestibular apparatus in all functions including whole cross-striated musculature and vegetative nervous system (VNS). Effect reactions induced by the infrasound stimulation of the labyrinth are similar to the symptom complex induced in case of motion disease; apparently, it can be attributed to the infrasound motion disease. Taking into account the tight relationship of vestibular analyzer with VNS centers and dorsal vagus nucleus, one can suppose that the vegetative disturbance development is basically determined by the vestibular-vegetative interaction activation.

Basic objective and subjective signs of the infrasound exposure and its harm and health risks classification is provided by Table 3.3.

Table 3.3 - Risk ranges of infrasound exposure (Izmerov N.F. et al, 1997)

Risk range	Frequency, sound pressure level, exposure time	Effects
1 fatal levels range	180 - 190 dB	Fatal effect (lung alveoli rupture)
2 extreme effect range	0 - 20 Hz < 140 - 150 dB 90 s	Middle ear pressure sensation.
	50 - 100 Hz > 154 dB 2 min	Headache, strangulation, caught, fogginess vision, fatigue, strong chest pressure sensation, salivation, swallowing pain. Tolerable limit symptoms
	100 Hz 153 dB 2 min	Nausea, giddiness, discomfort, skin redness.
	60 Hz 157 dB 2 min	Caught, strong chest pressure sensation.
	73 Hz 150 dB 2 min	Strangulation, salivation, swallowing pain, giddiness.

	0 - 50 Hz < 145 dB 2 min	Chest vibration sensation, mouth dryness, breath rhythm change, general fatigue, unreal false feeling. Below voluntary tolerance limit.
3 high health risk range even for periodic exposures	1 - 20 Hz 140 - 145 dB	Chest and abdominal cavity percussion is resulted by jet engine operation, the state of sea sickness is occurred, and vestibular disturbances are developed including static kinetic disorders, giddiness, and nausea. In case of long term exposure the development of asthenia, general fatigue, mental workability decrease, irritability, sleep disorders were found; in some cases mental disorders are occurred due to anxiety and fear.
3-_ high health risk range for relatively long-term exposure	2, 4, 8, 16 Hz 134, 129, 126, 123 dB 15 min	Subjective sensorial somatic vegetative discomfort: nausea, giddiness, pressure and massage of tympanic membranes, fever-like tremor, movements in the area of stomach and intestine, chest pain, visceral pain, headache, eye pain, anxiety, salivation, transient stiffness of palate and facial skin of apparent sensorial cortical genesis, voice modulation of limbic genesis. These signs indicate to the syndrome of infrasound (hypothalamic diencephalic) crisis. Objective reactions: middle ear mucosa hyperemia, static kinetic stability decrease, vestibular vegetative reactions (systolic arterial pressure decrease, pulse rate decrease etc); expressed decrease of CNS activation according to the coefficient of inter-hemispheric asymmetry. Increased reactions of aural analyzer in case of infrasound frequency increase and increased sensorial and CNS reactions with frequency decrease.
	10 Hz 135 dB 15 min	Expressed sensorial somatic vegetative discomfort: headache, giddiness, tympanic pressure, internal organ oscillation sensation, mouth dryness, breath obstruction.
4 moderately elevating health risk range	110 -120 dB	Several minute exposure is not health harmful. Longer exposure can induce follow-up effects in vestibular and aural analyzer and other body systems.
	2, 4, 8, 16 Hz 115 dB 1 and 5 hours	Interfering, irritating effects, moderate discomfort: sleepiness, headache, ear "jamming", body vibration sensation. Complains are increased with the frequency decrease. Unfavorable effects in many physiological indices. Confident correlation to subjective perception expressiveness and vegetative, stabilometric and other indices of functional state of the organism.
5 significant risk of chronic health disorders, especially if combined to other factors	100 - 110 dB 16, 105, 1 hour	Complains to interfering, irritating effects, giddiness, nausea, irritability, sleepiness, ear whistling, headache. Objective signs of decreased attention, static kinetic stability, pulse rate decrease, CNS functional activity decrease (inter-hemispheric asymmetry coefficient data)
	8, 16 Hz 100 dB 1 hour	Complains to throat scratching, cough, noise and pain in ears, fatigue, sleepiness, absent-mindedness. Physiological reactions are unchanged.
	8, 16 Hz 90 - 100 dB	Short time exposure is not health harmful; daily exposure results to complains and discomfort. Significant increase of spontaneous abortions rate (from 11% to 17%) and pregnancy complication rate (8 - 22%) in young female workers exposed to combined low intensive factors: 75 dB "A" noise and 8 Hz infrasound of 90 dB.
6 unclear and hard detectable health risk range	8 - 16 Hz < 90 dB	Isolated short/long time exposure is not heath harmful. Combination with noise and vibration as well as with nervous emotional tension can significantly amplify negative infrasound effects.
7 ecologically unfavorable population effect range for populated areas	16 Hz 109 dB	Significance of the population exposure was confirmed by the difference of complain rates (disturbances of day and night rest, poor sleep, frequent headaches). Infrasound causes interfering and irritating effects and induces functional disturbances.

Note: SAP - systolic arterial pressure, PR - pulse rate, CFJI - "critical frequency of joint images" test. > 150 dB are completely intolerable for examinees.

Basing upon original studies and literature references, the Research Institute of Labor Medicine has developed the concept of pathological pattern for the infrasound exposure of the human organism. This pattern is very comprehensive, however some basic statements can be emphasized.

The peculiar feature of the infrasound damage is the development of combined inter-related pathological processes. One of such processes is pre-caused by regularities of general adaptation syndrome and the other one is pre-caused by the alteration of the cerebral nervous formations, endocrine target organs and internal organs. The major pathogenetical part of this process is the development of tissue hypoxia resulted from cerebral hypertension caused by liquor hemodynamic and microcirculatory disturbances. The universal consequence of hypoxia is the membrane disorganization resulting to the enzyme leakage from sub-cellular structures and cells into the tissue liquid and blood; this is the main point of secondary hypoxia alteration of the tissue (Izmerov N.F. et al, 1997).

3.1 Sensorial (analyzing) systems of possible perception of low frequency acoustic oscillations

3.1.1 LFAO aural reception

Sensorial systems involved in the organism reaction to LFAO include aural system (Gierke H.E. von, Nixon C.W., 1976; Pimonow L, 1976), even despite of the fact that aural perception thresholds of LFAO are in the range of significant intensities (Yeowart N.S., 1976).

In early 1980th, large number of studies has been elaborated to investigate the noise influence in aural organ for the aural frequency band; issues of aural perception localizations in the cochlear spiral were also partially investigated for different sound frequencies. The analysis of literature data demonstrates that the lower cochlear part would be damaged by high frequency sounds (4000 Hz and more) and the upper cochlear part would be damaged by low frequency sounds (500 Hz and less). However, number of references indicates that this localization is not completely accurate. Rather severe damage is most common, especially if it was inflicted by low sounds.

The hear loss resulted from upper cochlea damage would never be complete. Animals always react to low sounds, if these sounds are rather powerful. If the spiral organ in lower cochlea is absent, the high frequency sounds will not be perceived at all. If the spiral organ is absent in the upper cochlea, the low frequency perception would be decreased. Nevertheless, loud low frequency sound will be perceived if the spiral organ is present in the lower cochlea. The hear loss due to the upper cochlea damage would not be complete in all cases.

Thus, these data change the common consideration on the symmetrical receptor structure distribution in the cochlea spiral, which receptor structures perceive high and low frequencies, if compared to Helmholz consideration. Apparently, the cochlea perceives low frequencies by the whole length of the spiral organ. High frequencies are perceived by the lower cochlea only. V.F. Undritz et al (1935) have established that sound intensity and its duration determine the damage severity.

The low frequency oscillation influence in the functional state of the aural analyzer was considered by a significant number of studies. Authors provide data on subjective sensations, aural threshold changes for different parameters of the infrasound, but elaborated studies do not inform about the mechanism of infrasound effects in spiral organ and pre-portal formations.

EPA publication on Criteria of the health and well being effects of noise (1973) provides the analysis of available data regarding LFAO effects in the aural analyzer and concludes to the statement that < 130 dB infrasound is not seriously harmful for the aural organ. For high intensities (> 130 dB) more serious harm can exist.

G.C. Mohr et al (1965) consider to be acceptable exposure levels of < 150 dB within 2 minutes. < 144 dB infrasound has not the aural threshold shift until the exposure time was below 10 minutes. >150 dB levels are the limit of human tolerance.

In case of the LFAO exposure, the reflex pressure has occurred in the middle ear. For instance, three examinees have mentioned the periodical sensation of tympanic scratching. The tests with low sounds of maximal intensity have demonstrated the induction of vomiting, vision field changes; two persons have felt the mild pain in the middle ear. The fatigue has persisted in the next day after the testing.

G. Bekesy (1936), H.E. von Gierke (1953) have established the pain threshold to be ~ 179 dB for static pressure, 165 dB at 3 Hz and 140 dB at the range of 15 Hz to 100 Hz and more.

C.W. Nixon (1974) reports that ~ 125 dB level induces the tympanic massage sensation coinciding to the infrasound frequency. Soon after that, the pressure sensation has occurred and followed membrane filling can be noted via mild redness of its surface. The followed increase of the affecting level can be accompanied by the ear discomfort. To evoke pain sensation in the human ear, very high infrasound levels are necessary. Some examinees have been observed to develop transient shifts of the aural threshold and aural threshold recovery has been reached within 30 minutes after the exposure termination. The pain threshold is ~ 150 dB at 10 Hz and it increases to 175-180 dB for static pressure. The author considers the ear pain irrelative to the sensitivity. Infrasound exposure can induce pain at levels, which are out of aural function danger. Any form of the ear pain felt at the time of the infrasound exposure has to be considered as the

indication to the excess of the tolerance of the mechanical system, so the exposure must be terminated and never tried again.

The author insists that experimental data are insufficient for this issue and that aural organ is poorly sensible to the infrasound. The following maximum permissible levels were proposed: 150 dB at 1–7 Hz, 145 dB at 8–11 Hz and 140 dB at 12–20 Hz. Maximal duration of the exposure is 8 minutes with 16 hours rest between exposures. The application of good quality bushes will give the opportunity to increase permissible levels for 5 dB for the same duration of the exposure. >150 dB level exposure has to be avoided even in case of maximal aural protection.

C.Q. Stockwell et al (1969) are sure that low frequencies induce less aural loss and lower damages of the lash epithelial cell than high frequencies of the same intensity. A. Moller (1975) confirms the opinion of C.Q. Stockwell et al regarding the lower harm of low frequencies if compared to higher frequencies of the same level.

R.H. Slarve, D. Johnson (1975) have done volunteer studies. The < 144 dB infrasound exposure of 1 Hz to 20 Hz frequency band was tried within 8 minutes in four males. Any objective harmful infrasound effect was not found including audiogram results. However, all examinees have felt non-painful "pressure increase" in the middle ear, which effect has disappeared after the exposure termination. The energy absorption in the middle ear structures is possible via tympanic membrane movement and it is felt like pressure. Authors have concluded that < 144 dB infrasound exposure is safe for healthy people within 8 minutes at least and that more longer exposures are safe too.

P. Borredon, J. Nathie (1974) has not observed significant audiogram changes in 13 young persons exposed to sinusoidal sound oscillations of 7.5 Hz and 130 dB intensity (50 minutes exposure; audiogram done one hour after the exposure termination).

According to J. Tonndorf (1950), G.C. Mohr et al (1965), C.W. Nixon (1974), D. Johnson (1974) and others, only insignificant transient changes of the aural threshold can be observed due to the exposure to the infrasound of middle and large intensities. If any, these aural threshold changes are rapidly mitigated to the initial level.

1970th - 1990th experiments have involved LFAO of 10 Hz and 20 Hz, which infrasound has amplified the bioelectric activity in the aural area of the brain cortex, changed pulse rate and breath rate, cutaneous resistance, and evoked nictating reflex as well. However, it is notable that such phenomena have been found at 80–100 dB, which is several orders of magnitude less than aural thresholds of low frequency acoustic oscillations (Mozhykhina N.A., 1979; Okai O., 1986).

According to Samoilov et al, the presence of so-called "sub-sensorial" reactions is stated for acoustic oscillations of 500 Hz and more, which was long before mentioned by G.V. Gershuni (1945). In scull cerebral trauma survivors, the exposure to acoustic oscillations of 50 dB below their aural threshold has induced the reflex mydriasis. For sound pressure levels of 40 dB below the isophone threshold the structure of bioelectric cerebral activity has been changed (alpha rhythm depression and beta rhythm increase). The nature of "sub-sensorial" reactions was correlated (Gershuni G.V., 1945, 1946, 1949) to the existence of extra-cochlear CNS pathways of the conduction of acoustic irritation information. These facts should not be recognized as the argument for high sensitivity of aural sensorial system to LFAO, because aural thresholds are frequently higher than thresholds of vegetative and other "sub-sensorial" reactions. That is why their investigation itself will not confirm or object the involvement of the aural system into the perception of low frequency acoustic oscillations. The investigation of other responses of aural receptors to LFAO is necessary in addition to sensation examination.

The significant portion of studies devoted to the experimental examination of abilities of sensorial perception of LFAO was tried in aural organ of human (Bekesy G. von, 1960, 1963, 1973; Yeowart N.S., 1974, 1976).

In early 1930^{th}, G. von Bekesy (1936) has demonstrated the human ability of aural perception of LFAO of significant intensities and frequencies of < 20 Hz. If the sound pressure is above 140 dB, the examinees have felt touch sensation together with sound perception. Using directional LFAO sources, it was possible to separate aural and touch sensations and to obtain threshold curve of aural sensitivity of human for 2-20 Hz band (Bekesy G. von, 1963).

Later studies have been devoted to LFAO exposure at 1-100 Hz and 140-154 dB sound pressure levels; the pain and pressure sensations were noted as well as the aural threshold elevation for 3-5 dB at high frequency band (Alford B.R. et al., 1966; Gierke H.E. von, 1974; Nixon C.W., 1974; Pimonow L., 1976).

Currently, it is accepted that human aural organ is able to perceive acoustic oscillations of 2 Hz and more, however, the "tone" sensation appears from 16-20 Hz. In mice, rats, guinea pigs and rabbits the lower frequency border of the aural perception (determined by behavior reactions) is 50-60 Hz (Bioacoustics, 1975; Baru A.V., 1978, Dallos P., 1985), whereas it is much lower for birds (2 Hz) (Kreithen M.L, Quine D.B., 1979; Morozov V.P., 1987; Shermuly L, Klinke R., 1990). Such difference is probably related to structural functional peculiarities of peripheral compartment of aural analyzer of different animal species (Bekesy G. von, 1963; Bioacoustics, 1975; Bogoslovskaya L.S., Solntceva G.N., 1979; Shepperd G., 1987; Vartanyan I.A., 1990).

The other studies have determined absolute LFAO aural thresholds in human. To obtain high sound pressure levels, they applied different sources of low frequency oscillations including

mechanical pistons, thermophones, headphones, loud speakers inside acoustic chambers. These studies were generalized by N.S. Yeowart (1976), taking into account original data of aural thresholds (Yeowart N.S. et al., 1967, 1969; Yeowart N.S., Evans M.J. 1974; Yeowart N.S., 1974). The comparative analysis of the obtained results has given the opportunity to draw the curve of LFAO aural perception.

The threshold isophone was approximated by two lines of different slopes: 12 dB per octave for 0.1-20 Hz and 22 dB per octave for 20-100 Hz range (Figure 3.1). B. Prazak (1974) has reported lower LFAO aural thresholds at 4 Hz and 8 Hz: 87 dB and 82 dB, respectively. In all studies, monoaural thresholds were for one order of magnitude higher than bi-aural ones. The similar loudness ratios at low frequencies were not such regular as at high ones; all curves have coincided at 1 Hz, which point corresponds to the sound pressure level of 160 dB (Yeowart N.S., 1976).

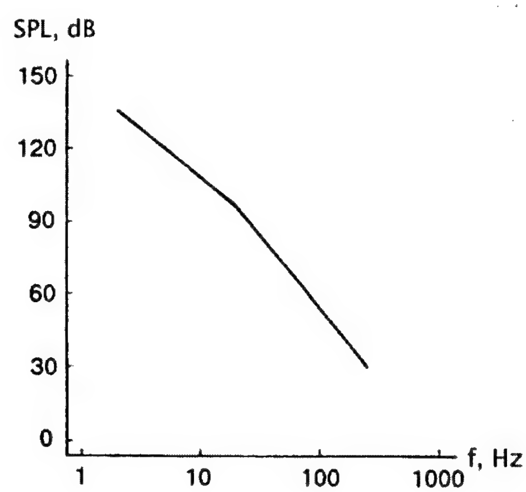


Figure 3.1 - Threshold isoline of aural human perception of LFAO (from Yeowart N.S., 1976)
Abscissa axis: frequency, f, Hz; ordinate axis: sound pressure level, SPL, dB

The objective examinations of cochlear function have provided data similar to that obtained from psycho-physiological studies. D.E. Parker (1976) has established non-linear relationships of the relative variation of the lateral shift of stirrup versus pre-lymph pressure at low frequencies. Similar dependencies were revealed for changes of the oscillation amplitude of tympanic membrane and hammer for LFAO exposure to different intensities (Densert B., Densert O., 1987).

LFAO of 100 Hz and more have induced the generation of receptor potentials in hairy cells of apical part of guinea pig cochlea. The amplitude of such potentials has non-linear increase with the increase of the acoustic sound pressure. In such case, the quality factor of amplitude-frequency characteristics of receptor potentials was decreased, which has certified to the decrease of the frequency separation of receptor responses of hairy cells (Dallos P., 1985).

Low frequency acoustic oscillations of octaval bands of 4-250 Hz have induced reversible change of nuclei volume, cytoplasm enlargement and RNA amount decrease in hairy cells and neurons of spiral ganglia in case of 90-120 dB exposure within long period of time (more than 1 hour) (Alexeev S.V. et al, 1986; Nekhoroshev A.S., Glynchikov V.V., 1990). In the same conditions, the reversible microcirculation changes of tympanic membrane and vascular stripe were recorded for LFAO exposure at 4 Hz (Nekhoroshev A.S., 1985; Anichin V.F., Nekhoroshev A.S., 1987). To get detailed understanding of these results, these publications are provided in almost full text below (see petit font text).

Low frequency acoustic oscillation effects in aural system receptor cells (Nekhoroshev A.S., 1985)

To evaluate the functional state of aural analyzer receptors narrow band (1 octave) low frequency noises of average geometric frequencies of 3.5 Hz and 63 Hz and 110 dB were applied. Experimental studies have been tried in 36 guinea pigs via three series of different exposure duration at each of noted frequencies: 30 minutes, 3 hours and 40 days (3 hours/day).

The pathological effects were evaluated basing upon the examination of nucleonic acids and "rhythmic functional nuclear pulsation process" in hairy cells together with karyometry examinations. These examinations are considered to be most convenient because nucleonic acids are important for living activities of all organs and tissues to provide albumin synthesis. Therefore, the content of these acids can provide information regarding functional cellular activity. The "rhythmic functional nuclear pulsation process" was investigated by a number of studies devoted to LFAO effects. The proposed technique gives the opportunity to objectively observe nuclei size changes, for instance, via the calculation of their volumes. The studies have demonstrated that the effect of narrow band noise (1 octave) of 63 Hz average geometric frequencies and 110 dB intensity consists in expressed changes in almost whole cochlea excluding its apical part. In lower cochlear parts (lowest and middle lower parts) both enlarged and diminished nuclei were detected. Enlarged nuclei had light color (decrease of the diffuse RNA concentration in karyplasm) and peripheral shift of small nuclei and DNA stones. Diminished nuclei were intensively painted, which indicates to the increased diffuse RNA concentration in karyplasm. Small nuclei and DNA stones are hardly visible on the background if the intensive color. Diminished nuclei were noted for exposure duration of 3 hours and 40 days (3 hour/day) only. The 30 minutes exposure was found to show only "functional enlargement of nuclei" of exterior hairy cells.

After the visual examination, karyometry tests were tried. Each cochlear compartment was counted for 10 nuclei at least. Data of same experimental

series were summarized for each compartment separately and statistically processed. Karyometry examination results are shown by the Figure (100% level is the average volume of exterior hairy cell nuclei for each cochlear compartment of control animals.

The obtained data indicate that changes are present in almost whole cochlea including three lower compartments; only apical compartment was intact. Diminished nuclei have dominated at the cochlear basis and involved two lower compartments. The change expressiveness was directly correlated to the exposure duration.

Similar studies were elaborated for 31.5 Hz average geometric frequency noise of 1 octave band. The exterior hairy cell nuclei at "functional enlargement" state were examined. Diminished nuclei were usually absent. The short time exposure (30 minutes and 3 hours) were specific to changes in three compartments including the cochlear basis; in case of the long time exposure (40 days, 3 hours/day) changes were found in whole cochlea including apical compartment. However, the expressiveness of changes was lower in the basis whereas middle cochlear compartments were changed more expressively.

Therefore, the acoustic exposure of noted parameters induces moderate changes of exterior hairy cells including moderate "functional enlargement" of cellular nuclei in the whole cochlea.

Thus, low frequency acoustic oscillations of rather high intensity (up to 110 dB) have induced expressed functional disturbances of aural organ receptors. In case of the exposure to narrow band (1 octave) noise of average geometric frequency of 63 Hz the changes were completely correlated to previous data regarding dissemination and expressiveness of changes versus frequency components of the noise. The applied acoustic factor has induced changes in the whole cochlea with highest expressiveness in its lower and middle compartments. 31.5 Hz average geometric frequency noise of 1 octave band has caused changes of different character: changes were found in the whole cochlea, especially at long time exposure. At the same time, the expressiveness of detected shifts was maximal in middle cochlea. Such noise was found to be less traumatic than that of 63 Hz frequency. However, the highest expressiveness of middle cochlea changes indicates to some mechanism difference from higher spectrum noises. Therefore, one can suppose that the noise of such parameters (31.5 Hz, 110 dB) is lowest aural noise and, probably, its effect is not explained by the "running wave" theory.

Therefore, to prevent persistent changes of aural function, the LFAO exposure of high intensities has to be time limited by 3-4 hours. In case of daily exposure for < 3 hours, the aural receptor changes are of functional character.

On the mechanism of the acoustic load in aural system (Alexeev S.V., Anichin V.F., Nekhoroshev A.S., 1986)

At present time, noise is the one of most common unfavorable industrial factor. Functional morphological studies are important for the assessment of biological shifts in aural system tissues even in case of relatively low noise load. The specific and indicative response of aural receptor sells to the acoustic stimulation is the so-called "rhythmic functional pulsation of nuclei", which was investigated in details by a number of authors.

The functional morphological study was tried applying histochemical and electronic cytochemical techniques. Karyometry examinations were widely

applied too. Besides, the vascular reaction of the tympanic membrane and aural bones was examined in case of the acoustic load. Experimental animals were exposed to high frequency (2000 Hz, 4000 Hz) sound and narrow band noise of different frequencies (1000, 500, 250, 63 and 31.5 Hz). Intensities were in the range of 100 dB to 110 dB. Both acute and chronic experiments were elaborated. The exposure duration was 0.5 h to 12 h (acute experiments) and 40 days (3 h/day, chronic experiment).

Cochleae isolated applying J. A. Vinnikov and L.K. Titova technique were examined to find changes induced by the acoustic load including tests of the following biological substances in the spiral organ and vascular stripe: nucleonic acids, monophosphorous esterase, acetylcholinum esterase. Besides, the isolation of tympanic membrane and aural bones was done, which tissues were processed to detect the alkaline phosphatase applying Gomori technique. Such tests have given the opportunity to assess the enzymatic activity in vascular walls and structural elements of vessels. The painting intensity of vessels indicates to the vascular reaction to the acoustic load. 3 phases of functional changes can be found depending upon the noise exposure duration.

In case of the short time noise (3-4 hours) hairy cells of the spiral organ are in the state of "active functioning" which is morphologically demonstrated by the dominant process of the hairy cell nuclei enlargement it was noted, when examining processes of "rhythmic functional pulsation of nuclei". For the first time, this reaction was detected by A. Benninghoff.

In case of 5 hour acoustic load, hairy cells are apparently able to switch off the excitation state. The morphological sign of this process consists in "functional diminishing" of hairy cell nuclei.

In case of long time acoustic exposure (up to 12 h in acute experiment), hairy cells of the spiral organ do not react to the applied acoustic stimulation. It is certified by the strong decrease of nucleonic cell content (the nucleus and cytoplasm are light colored). In such case the nucleus is not enlarged. In aural cerebral neurons of the brain cortex similar events are happen.

Karyometry examinations have demonstrated the quantitative dependence of hairy cell nuclei and aural neurons reaction to the acoustic load of different duration. In the spiral organ the nuclei volume was ~ 200% of control (functional enlargement) in case of the relatively short exposure (< 4 h). At hour 5 of the exposure, the averaged nuclei volume was 85% of control ("functional diminishing"). For longer exposures (up to 12 h) the nuclei volume was almost equal to the control one (termination of the acoustic stimulation reaction).

In the aural cortical area, the neuron nuclei reaction was different from that in the spiral organ. The gradual increase of the nuclei volume simultaneously to the acoustic load duration increase was found; most expressed reaction was detected in layers IV and VI. The nuclei volume diminishing was found for longest exposure (12 h).

Such cycles of aural system reaction to the acoustic load can be observed via the state of other biologically active substances. In case of the exposure time below 6 hours, the rather high activity of monophosphorous esterases has persisted and glycogen content is slightly decreased. Only > 6 hours load the content of these ingredients is decreased.

The observed functional transformations of hairy cell nuclei were specific to the frequency characteristics and exposure duration. In case of low frequency noises (31,5 Hz and 63 Hz) of 110 dB, such changes (nuclei reaction) was disseminated in the whole cochlea. Changes were not found in

the apical cochlea only. Depending upon the exposure duration, the nuclei reaction was different. In case of the single short time exposure (30 minutes), the moderately expressed "functional enlargement" of exterior hairy cell nuclei was observed. In case of longer exposure (3 h) to the narrow band (octaval) low frequency noise (63 Hz), some diminished nuclei have appeared. However, the narrow band (octaval) low frequency noise (31,5 Hz) has not induced "functional diminishing" of hairy cell nuclei including both acute and chronic experiments.

40 days exposure (3 hours/day) to noises of mentioned parameters has not induced degenerative atrophic changes of the aural receptors; only functional morphological changes have been observed. The frequency increase from 250 Hz to 4000 Hz has been found to induce similar functional nuclei transformations, but these changes were localized close to the cochlear basis. The higher frequency is applied, the narrower site of changes is found, but it is always close to the cochlear basis.

Despite cochlea apparatus, the middle ear system also reacts to the acoustic stimulation; this reaction is essentially expressed to low frequency exposure. The lowest examined frequency (31.5 Hz) exposure to 110 dB has been found to induce hemorrhages in the tympanic bulla cavity (more frequent for > 3 h exposure). Such events in the middle ear were absent in case of higher frequency exposure at 63 Hz to 4000 Hz.

Applying electronic microscopy, the stereocele slope was found for any duration of the acoustic stimulation. For short time exposure the moderate enlightening of the cytoplasmatic matrix was observed as well as the concentration of mitochondrias having high electronic density in sub-cuticular and sub-nuclear areas. For long time exposure the cytoplasm enlightening was strongly amplified; mitochondrias were enlarged and enlighten.

The electronic cytochemical technique was applied to examine the acetylcholinum esterase activity change, which substance is important for trans-synapses transfer of the nervous impulse. In case of 4 hour exposure, the activity of this ferment was decreased in the synapses bubble area placed inside the hairy cell body; in inter-synapses slits of nervous endpoints it persists to be rather high. In case of > 6 hour exposure, the ferment was almost undetectable in synapses bubbles and its activity in inter-synapses slits was strongly decreased. It certifies to the fact that relatively short acoustic stimulation is specific to apparently small nervous pulsation disturbance. The disturbance of this process has occurred in case of > 6 hour exposure. Basing upon obtained data, one can conclude that the acoustic load of high intensity is responded by the aural system via the complex of biological reactions, which are exposure duration dependent. Most specific changes occur in the receptor compartment (spiral organ) as well as in the sound conducting system of the aural analyzer. Spiral organ responses to the acoustic load are specific to three phases as follows:

1. In case of relatively short acoustic load (< 4 hours), receptor cells are specific to increased metabolism of biologically active substances. The hairy cell is in "active functioning" state. It was certified by the predominant functional enlargement of hairy cell nuclei and relatively high activity of monophosphorous esterases (alkaline phosphatase, essentially). Nervous pulsation is hardly disturbed, because the acetylcholinum esterase activity is rather high in inter-synapses slits. Such "resistance" to the elevated load is apparently related to the glycogen presence, which decay happens under anaerobic conditions; its biological importance is increased if the oxygen deficiency exists.

2. 6 hour acoustic load can be considered as critical one, because hairy cell is apparently switched off from the excitation state and reparative processes are initiated. The index of reparation is the predominant "functional diminishing" of hairy cell nuclei and relatively high activity of alkaline phospotase. Nervous pulsation is also disturbed which is certified by the acetylcholinum esterase activity decrease in inter-synapses slits of nervous endpoints.

3. In case of the long acoustic load (> 6 hours) the strong exhaustion of all biological resources occurs and hairy cells do not react to the acoustic load. In the aural area of brain cortex and intermediate compartments of the aural system (excluding aural nuclei), changes are increased simultaneously to acoustic load duration increase. However, in case of long acoustic loads, the whole aural system is specific to the strong decrease of biologically active substance contents. The sound conducting system reacts to low frequency acoustic oscillations. For instance, in case of narrow band (octaval) low frequency noise at 31.5 Hz, middle ear cavity hemorrhages were observed, which was not recorded in case of higher frequency noise exposure.

Thus, maximal duration of high frequency noise exposure is 3-4 hours in case of ~ 100 dB intensity. In case of 3-4 hours low frequency noise exposure, the possible intensity is ~ 110 dB. After such exposure, the sound rest of ~ 1 hour is necessary. This time is necessary to complete reparative processes in the aural organ.

Infrasound effect mechanism in aural labyrinth receptors (Nekhoroshev A.S., Glinchikov V.V., 1990)

Infrasound acoustic oscillations are poorly investigated. The issue of the effect mechanism is unclear for both the whole organism and for the aural labyrinth. To investigate changes induced by the infrasound in receptor cells of semicircle channels, utricle, saccule, and in receptor elements of the cochlear compartment of the aural organ the experimental study was tried.

Technique. 18 guinea pigs were exposed to 8 Hz and 16 Hz infrasound of 90—120 dB inside the specialized acoustic complex composed of infrasound generator and sound isolated chamber. The sound pressure level was monitored by noise measurement equipment (Bruel and Kjaer). The exposure duration was 1, 5, 10, 15 and 25 days, 3 hours/day. The experimental animals were chosen according to their aural characteristics. Aural thresholds of guinea pigs are almost the same as human ones, especially at 1 kHz frequencies. Basing upon the comparison of threshold curves of guinea pigs versus human, one can suppose that differences will not be high at < 50 Hz band. The guinea pig cochlea has 4-4.25 turns and is almost completely positioned in the tympanic bulla cavity, which makes it easy to manipulate. Finally, the majority of previous studies of aural mechanisms was tried in these animals.

Animals were decapitated and visceral bones were separated. The tympanic bulla was open and bony capsule of the cochlea was dissected in the apical area to have better penetration of the fixing solution. Further manipulations were done applying stereoscopic microscope (MBS-2) inside the glass chamber. The whole labyrinth was separated together with its vestibular and cochlear compartments. The isolated cochlea was used to separate nucleonic acids applying Eynarson technique to assess processes of "rhythmic functional pulsation" of nuclei and nucleonic acid contents in exterior and interior hairy cells. Ampules of 3 semicircle channels were taken

for electronic microscopy. Slices were prepared by ultratome (LKB-III) and JEM-7A electronic microscope was used for slice examinations.

After 3 hour infrasound exposure semicircle channel cells were changed. These changes were of mosaic character and expressed by strong increase or decrease of nuclei volume with diminished nuclei appearance (Figure 3.2). Simultaneously to the change of form and sizes of receptor cell nuclei, the cytoplasm enlargement was observed with increased basophilia and vacuole occurrence.

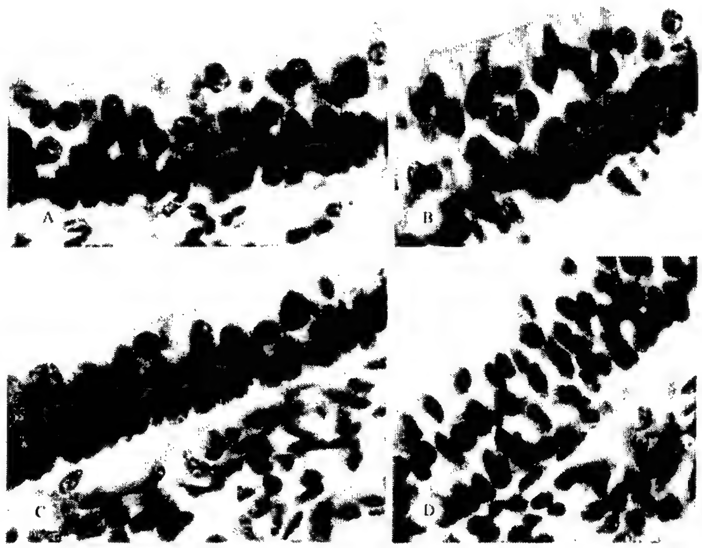


Figure 3.2 - Histological slices of utricle. 3 hours after infrasound exposure
A - initial phase of "functional nuclei pulsation";
B - moderately expressed nuclei polymorphism; C - expressed polymorphism of receptor cell of, type I; D — "functional diminishing" of nuclei and expressed polymorphism

In nuclei of receptor cells of type I (utricle and saccule) the RNA content was decreased whereas receptor cells of type II were unchanged. Foot cells were unchanged. The electronic microscopic examination has demonstrated that ultrastructure changes are less expressed in receptor cells of semicircle channels, if compared to pre-portal receptor cells. The cytoplasm of pre-portal cells was found to have the decreased ribosome count, expanded membranes of Holdgi complex and moderately expressed mitochondria enlargement. In nuclei of cells of "functional enlargement" the chromatin was moved to the nuclear membrane area. Nervous endpoints in the basis of receptor cells were slightly changed, however, the mitochondria with enlighten matrix and moderately shorten crests could be detected.

Most expressed changes were noted in hairy cells of the spiral organ, especially in the middle cochlear compartments, where "functional pulsation" of hairy cell nuclei was noted by the chromatin re-distribution, diffuse RNA concentration decrease in karyplasm and cytoplasm and by nuclei size increase. together with these findings, the nuclei of intensive painting were detected. Such nuclei were frequent in exterior hairy cells, where "functional pulsation" was essentially expressed. (Figure 3.3a).

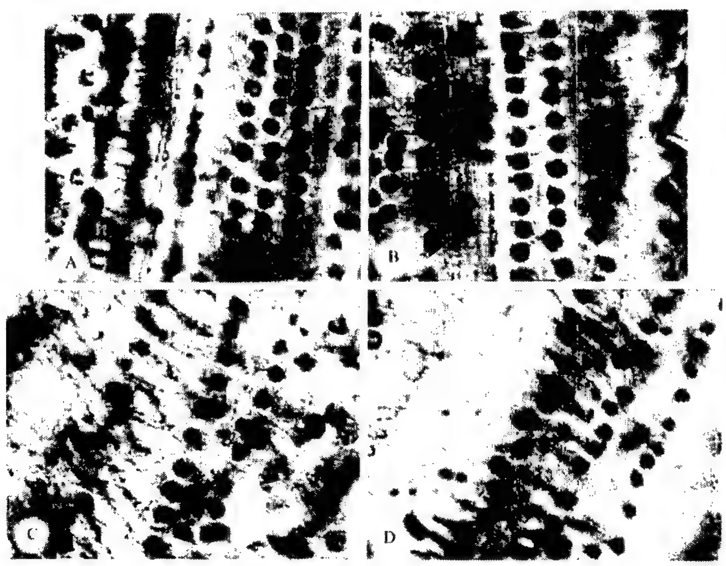


Figure 3.3 - Slices of spiral organ

A — expressed "functional nuclei pulsation" in exterior hairy cells versus interior ones; B - nuclei polymorphism of interior and exterior hairy cells at day 10 of the experiment; C — expressed nuclei polymorphism of exterior hairy cells of upper cochlea at day 15 of the experiment; D — expressed nuclei polymorphism of exterior hairy cells with RNA concentration increase in cytoplasm at day 25 of the experiment

Among cells of middle cochlea, cells with extended cisterns of Holdgi complex and enlarged mitochondrias were found, which crests were partially deformed. Nuclei of these cells were found to have chromatin re-distribution with accumulation at nucleus membrane.

After 5 day infrasound exposure, receptor cells of all 3 semicircle channels were specific to strong nuclei polymorphism; very large nuclei were detected as well as normal and "functionally diminished" nuclei. Such nuclei polymorphism was accompanied by enlighten cytoplasm and diffuse RNA concentration decrease in karyplasm and cytoplasm. In diminished nuclei, chromatin has composed large dark stones, which were placed close to each other. The enlargement and diminishing of nuclei in receptor cells of semicircle channels are correlated to "rhythmic functional pulsation" of nuclei as the response to the infrasound exposure. The electronic microscopy examination of these cells has revealed the ribosome count

decrease, strongly enlarged mitochondrias, deformations and ruptures of endoplasmic reticule membranes.

The revealed receptor cells changes are related not only to the direct infrasound effects in sensible cells, but also to the cellular nutrition disturbance due to the blood circulation disorders noted by blood stases, fine hemorrhages of emigration character, and destruction of vascular cells.

At day 10 of the experiment, practically all receptor cells of three semicircle channels were changed and come to the state of "functional diminishing". The polymorphism of cellular reactions to the infrasound exposure is determined by different sensitivity of these cells to the infrasound exposure. It is necessary to note the increased infrasound sensitivity of hairy cells of middle cochlea. Interior hairy cells have slightly reacted to the long infrasound exposure, though enlarged or diminished cells are also present. The described changes of exterior and interior hairy cells were of mosaic character and have been caused by partial RNA redistribution in the structure of "rhythmic pulsating" nuclei (Figure 3.3, b). Moreover, the long infrasound exposure (days 15, 25) has induced the increase of the diffuse RNA concentration in karyplasm and cytoplasm of damaged cells (Figure 3.3, c, d).

In case of 25 day infrasound exposure, in all three layers of exterior hairy cells, the nuclei diminishing was observed together with RNA concentration increase and strong movement of DNA to the peripheral area, where chromatin stones have created intensively galocyanin colored conglomerates. All described changes were reversible and damaged cells have gradually recovered after the exposure termination. The foot cells were intact to the infrasound exposure.

The study has demonstrated that 16 Hz exposure of 90-120 dB (3 hours/day) has induced morphological changes in receptor cells of all three semicircle channels. These changes are initially of the character of "rhythmic functional pulsation" of nuclei; thereafter, these changes result to nuclei polymorphism, which creates very variable morphological picture. Simultaneously to nuclei changes, the cellular cytoplasm is specific to basophilia and vacuole occurrence.

In case of the infrasound exposure duration increase, the number of changed nuclei is strongly increased and chromatin re-distribution occurs with its concentration in the nuclear center, which results to the nuclear diminishing. The cytoplasm basophilia in receptor cells is decreased, which is related to RNA synthesis disturbance.

After 10 days of the infrasound exposure, all nuclei of receptor cells of semicircle channels are changed, which certifies to their large sensitivity to acoustic oscillations of the infrasound band. Most sensitive cells are exterior hairy cells, where Holdgi complex cisterns were already enlarged at hour 3 of the exposure together with mitochondria enlargement with moderate crest deformations, RNA content decrease in nuclei, and chromatin re-distribution with concentration close to the nuclear membrane. The longer exposure (10-25 days) has induced changes in exterior hairy cells of the middle cochlea, where diffuse RNA concentration was increased in karyplasm and cytoplasm. At the end of the experiment (day 25) all layers of exterior hairy cells had "functional diminishing" of nuclei. It is not excluded that described changes of hairy cells are accompanied by aural function disorder.

Thus, the study has demonstrated that changes induced in receptor cells of aural labyrinth and the grade of their expressiveness is basically correlated to the sound pressure level and infrasound exposure duration rather than to the infrasound frequency. In case of the infrasound exposure

at 8 Hz and 16 Hz (90-120 dB), the reversible "functional diminishing" of nuclei of labyrinth receptor cells was observed; it is supposed that this diminishing certifies to cell fatigue.

The increase of the sound pressure level to > 120 dB has induced irreversible changes of hairy cells morphology. The grade of their damage was determined by LFAO sound pressure amplitude. The localization of destructive shifts of hairy cells in the medial cochlea (Nekhoroshev A.S., 1985; Erokhin V.N., Glinchikov V.V., 1988; Nekhoroshev A.S., Glinchikov V.V., 1990) was unpredicted by authors. The obtained data certify to the absence of frequency selectivity for damaging LFAO effects in the aural organ (Anichin V.F., Nekhoroshev A.S., 1987).

Together with hairy cell damage, low frequency acoustic oscillations have induced expressed masking effect. Acoustic stimulation at 10-15 Hz and 100-130 dB has masked wide frequency band (up to 4000 Hz). In such case, the masking effect magnitude was 10-30 dB (Fink A., 1961). Such effects at 100-4000 Hz band are specific to acoustic oscillations of lower frequency (7-10 Hz) with sound pressure level of 120-140 dB (Jerger J. et al., 1966). The LFAO masking effect has significantly complicated routine operator work for distinguishing sound signals (Karpova N.I., Malyshev E.N., 1981).

Thus, the aural analyzer reaction to low frequency acoustic oscillations is proved in experiment (Yeowart N.S., 1974; Pimonow L., 1976; Alexeev S.V., Mozhukhina N.A., 1983; Nekhoroshev A.S., Glinchikov V.V., 1992). However, mechanisms of LFAO aural perception are still unclear.

The calculation of basiliar membrane oscillation amplitudes done in experiments and applying models has demonstrated that they are low at < 50 Hz frequencies (Bekesy G. von, 1960; Zwislocki J., 1961; Dallos P., 1984). Peri-lymph oscillations in cochlear stairs are co-phased at these frequencies. Small pressure difference in channels complicates the creation of the expressed maximum of the running wave (Densert B., Densert O., 1987). When analyzing the shape of the microphone potentials at low frequencies, E.G. Wewer (according to ideas expressed by P. Fletcher) has suggested that acoustic oscillations are distorted in the cochlea. It can originate to the overtone generation, which overtones are perceived by the internal ear (Wewer E.G., Bray C.W., 1930). Similar judgments were expressed by other researchers (Rzhevkin S.N., 1936). Spectral characteristics of applied acoustic oscillations are not provided by these publications. In such conditions, N.S. Yeowart (1976) has noted that electric cochlear reactions to high frequency harmonics are not excluded, which harmonics could be in the low frequency oscillation spectrum.

The formulation of statements regarding LFAO effect mechanism in aural organ is complicated by the absence of the single approach to the effective (acting) parameter of acoustic oscillations, which induces the sensorial response of hairy cells.

Dynamic pressure chambers used in the majority of experiments give the opportunity to assess the sound pressure effects only (Pimonow L, 1976). Basing upon this consideration, the majority of authors has considered the sound pressure amplitude as the effecting aural parameter (Gelfand S.A., 1984). The absence of reliable methods for measurement of media particle oscillation has not given the opportunity to reveal the importance of this oscillation for LFAO aural perception. Therefore, the air media particles oscillation is less justified than sound pressure, when considering the leading factor of LFAO aural reception (Goldstein M.N., 1980; Dallos P., 1984; Sheperd G., 1987).

Existing aural theories can not satisfactory explain the LFAO perception mechanism in aural receptors. The frequency selectivity of the peripheral compartment of aural analyzer is expressed poorly and aural thresholds are in the range of significant sound pressure levels. Together with this fact, "audible" low frequency acoustic oscillations of high intensity cannot be the adequate stimulation of hairy cells, because of the damaging issue. Acoustic oscillations of high sound pressure is more specific to damage rather than to the stimulation.

When searching the answers to the questions regarding LFAO aural perception, V.O. Samoilov et al (1994) has examined electric cochlear responses.

Microphone cochlear responses to low frequency acoustic oscillations (Samoilov V.O. et al, 1994)

Peripheral mechanisms of LFAO aural perception were examined applying recording microphone cochlear potentials. The LFAO metrology was properly addressed. Direct measurements of the oscillation shifts and power flux density in the non-formed LFAO wave area of the acoustic emitter were possible. It has provided the assessments of aural organ reactions not only to the sound pressure but also to the oscillation shift of air media particles.

LFAO are basically perceived by hairpin cells of the apical cochlea (Dallos P., 1984; Aural system, 1990). The issue of the importance of the microphone potential recorded in the opposite cochlear compartment (at its basis) to reflect electric activity of hairpin cells of the apical cochlea has been discussed in the literature (Wever E.C., Lowrence M., 1954; Gelfand S.A., 1984).

P. Dallos (1973) has demonstrated that if the electrode is positioned near the round window, the superposition of receptor potentials of separate hairpin cells is arranged in the spatially weighted way taking into account phasic relationships. In case of the LFAO exposure, phasic shift of receptor potentials in basal cochlear compartment is significantly higher than that in apical compartment, which results to the mutual amplitude distinguishing. Therefore, the input of receptor potentials of hairpin cells of the apical cochlear compartment to the microphone potential is more important if

compared to that from the basal cochlea. The microphone potential recorded at the round window is the filtered low frequency microphone response.

Due to complications of the visualization of microphone amplitude potentials at low frequencies, the spectral analysis of recorded electric signals was elaborated. The measurement accuracy for microphone potential harmonic amplitudes was < 6%.

The microphone response of the guinea pig cochlea was recorded at all examined frequencies. Microphone potential amplitude measurements were done for fixed frequency, sound pressure and power flux density. The dependencies of microphone potentials versus LFAO parameters (iso-frequency, isobaric and iso-intensive curves) were drawn as well as the microphone response curves for equal amplitudes.

Different authors indicate to variability of microphone potential amplitudes, which can reach tens of microvolts (Lawrence W., 1967; Dallos P., 1984). The magnitude of microphone response is determined by the position of the reference electrode at the round window, which is different in different animal experiments. This statement significantly complicates the correct application of variation methods of statistics, because these methods align differences. Therefore, the statistical analysis of recorded microphone responses should be elaborated applying parametrical criteria.

The present tests have established the dependence of microphone potential amplitudes versus the LFAO sound pressure. The increase of the sound pressure has induced the microphone potential elevation. For sound pressure levels of 0.2–1.0 Pa, the slope reflecting these dependencies is less than one for all frequencies excluding 1000 Hz. For increased sound pressure of 5 Pa, the microphone potential amplitude is strongly elevated and the slope is increased for several times at each frequency (Figure 3.4).

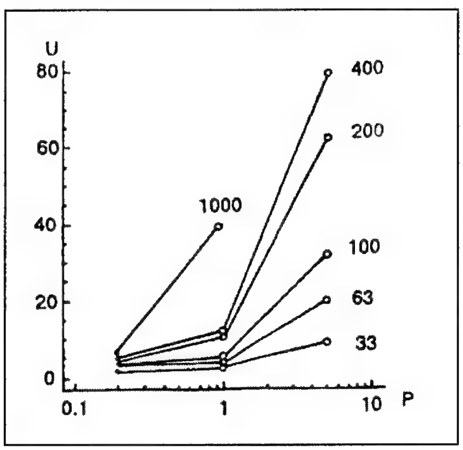


Figure 3.4 – Microphone potential amplitude vs. sound pressure: different frequencies (iso-frequency curves)

Abscissa axis: sound pressure, P, Pa; Ordinate axis: microphone potential amplitude, U, μV. Numbers at curves: frequencies, Hz

Similar dependencies were found for microphone potential amplitudes vs. frequency in case of constant sound pressure. According to charts

(Figure 3.5), in case of the frequency increase, the microphone potential elevation has occurred. The grade of electric response amplification was strongly increased in the range of high pressures.

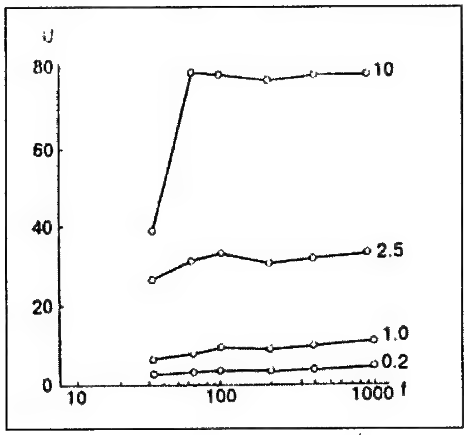


Figure 3.5 - Microphone potential amplitude vs. frequency: different sound pressures (isobaric curves)

Abscissa axis: frequency f, Hz; Ordinate axis: Ordinate axis - microphone potential amplitude, U, μV. Numbers at curves - sound pressure amplitude, P, Pa

The analysis of iso-amplitude curves (aural curves) has demonstrated that higher frequency is specific to higher sensitivity of the peripheral aural compartment. Microphone responses of the similar amplitude have occurred at lower sound pressures in case of the frequency increase (Figure 3.6). The slope of aural curves at low frequencies is > 6 dB·octave^{-1}.

Iso-intensive curves were different from isobaric ones (Figure 3.5) because of parallel "plateau" shape. Despite of different individual microphone potential amplitudes in different animal species, the trend of iso-intensive curves in different animals was the same. These curves reflect the trend of the independence of microphone potential amplitudes versus the frequency in case of similar power flux density, which independence has been found at 63-1000 Hz in all examined animals of the specific series.

When comparing iso-amplitude response curves (aural curves) at different sound pressures and power flux densities (Figures 3.6 and 3.10), significant differences were found. In the second case, curves of equal microphone responses did not have slopes to the high frequency range and they had the shape of almost parallel "plateau". It also certifies to the absence of the expressed dependence of cochlear microphone response vs. frequency in the range of 63-1000 Hz.

The statistically significant electric cochlear reactions were recorded for LFAO power flux density below 0.2 mW m^{-2}. The PFD increase has resulted to the expressed increase of microphone potential amplitude at all frequencies. The character of iso-frequency curves is illustrated by Figure 3.7. For all frequencies excluding 33 Hz, they were similar and in contrary to curves shown by Figure 3.4 could be fitted by similar logarithmic functions. At 33 Hz, microphone response amplitudes were significantly lower and confidently different versus responses at other frequencies.

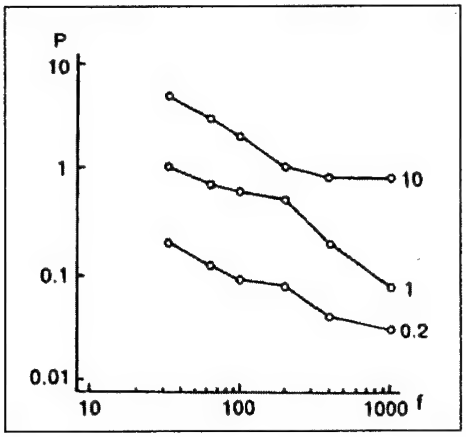


Figure 3.6 - Microphone response curves of constant amplitude versus different sound pressures (equipotential curves)
Abscissa axis: frequency, f, Hz; Ordinate axis: sound pressure, P, Pa. Numbers at curves - sound pressure amplitude, Pa

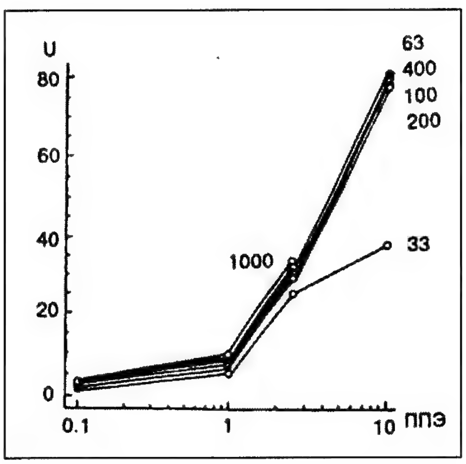


Figure 3.7 - Microphone potential amplitude vs. power flux densities at different frequencies (iso-frequency curves)
Abscissa axis: power flux density - PFD, mV/m²; Ordinate axis: microphone potential amplitude, U, μV. Numbers at curves - frequency, Hz

Different directions of the frequency dependencies for sound pressure and microphone potentials certify to less expressed relationship of microphone potential dynamics vs. sound pressure changes. If the electric cochlear responses in non-formed wave area were predominantly

determined by sound pressure value, at least the coincidence of the direction of curves shown by Figures 3.5 and 3.12 is expected.

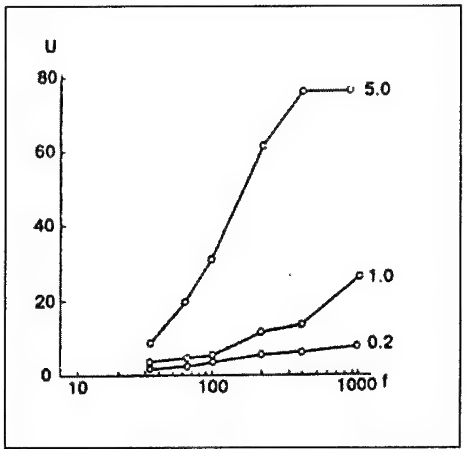


Figure 3.8 - Microphone potential amplitude vs. frequency at different power flux density (iso-intensive curves)
Abscissa axis: frequency, f, Hz; Ordinate axis: microphone potential amplitude, U, μV. Numbers at curves - power flux density - PFD, mV/m²

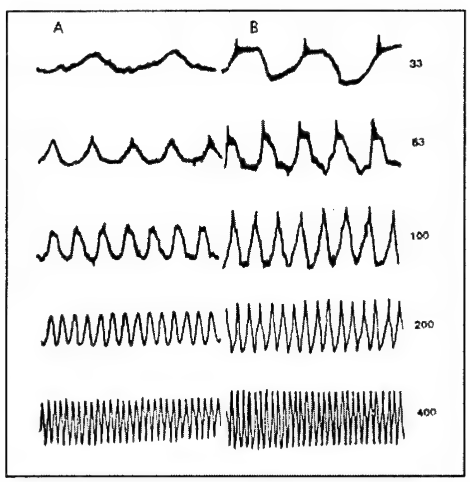


Figure 3.9 - Microphone cochlear potentials (guinea pig) in case of LFAO exposure of similar power flux densities - 1 mW/m² (A) and 10 mW/m² (B)
On the right - frequency, Hz. Calibration - 5 ms (A), 10 ms (B), 20 μV

Figure 3.8 confirms the expressed suggestion, which follows to the fact that microphone potential amplitudes at 63–1000 Hz are practically similar and determined by power flux density values. In the non-formed wave area, the oscillation shift value is constant and the sound pressure increase is accompanied by proportional increase of power flux density and microphone potential amplitude.

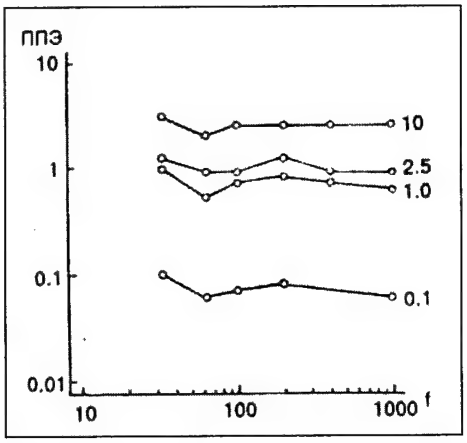


Figure 3.10 – Microphone responses of similar amplitude vs. different power flux densities (equipotential curves)
Abscissa axis: frequency, f, Hz; Ordinate axis: PFD, mW/m². Numbers at curves – power flux density, mW/m²

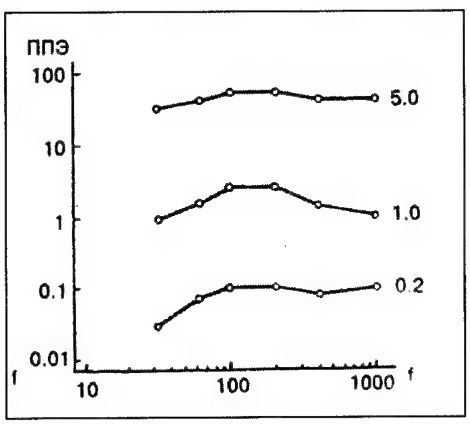


Figure 3.11 – Power flux density vs. frequency at different sound pressures
Abscissa axis: frequency, f, Hz; Ordinate axis: power flux density, PFD, mW/m². Numbers at curves – sound pressure amplitude, Pa,

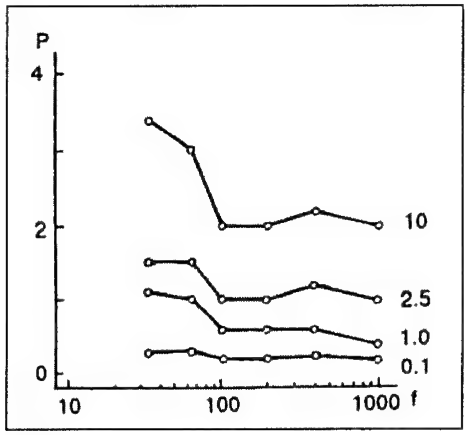


Figure 3.12 - sound pressure amplitudes (working area of the sound distinguished chamber) vs. frequency at different power flux densities
Abscissa axis: frequency, f, Hz; Ordinate axis: sound pressure, P, Pa. Numbers at curves - power flux density, PFD, mW/m²

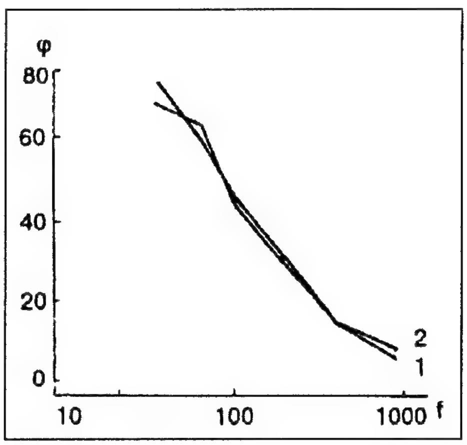


Figure 3.13 - Phasic shift angle (working area of the sound distinguished chamber) vs. frequency
Abscissa axis: frequency, f, Hz; Ordinate axis: phasic shift angle between sound pressure amplitude and oscillation velocity of particles, φ, degrees
1 - calculated via nomogram (Pimonow L., 1976),
2 - measurement results

The revealed differences of microphone cochlear potential dependence vs. sound pressure and power flux density rise the issue of acting (effecting) parameter, which determines LFAO aural effects in the non-formed wave area. This issue was risen earlier (Pimonov L, 1976; Yeowart N.S., 1976; Popov A.V., 1985; Vartanyan I.A., 1990). Such possible parameters were

attributed to sound pressure or oscillation shift of the media particles determining mechanical energy propagation.

The obtained data are the additional confirmation of oscillation shift of particles as the effective LFAO parameter (Ponomarenko G.N., 1992; Ponomarenko G.N., 1993). Though other groups of mechanic receptors have the major effecting factor of the shift, complex relationships between, sound pressure and media particle oscillation shift in the non-formed wave are often ignored. It is suggested that aural system reacts to low frequency acoustic oscillations of significant sound pressure levels. The inter-positioning of biological objects and acoustic generator is frequently not taken into account.

Experimental results indicate that the near-by acoustic field is predominant to be assessed according to power flux density, when considering aural system response (Ponomarenko G.N., 1992; Ponomarenko G.N., 1993). Being the vector parameter, the power flux density (Umov vector) contains the information about both the sound pressure value and the direction of its propagation (Umov N.A., 1874) and this value can be effective for aural system in case of identification and localization of the sound perceived by animals. The basic role of power flux density to form microphone responses was noted by G. von Bekesy (1960). Nevertheless, this suggestion was not confirmed in experiment at low frequency band.

The data obtained by V.O. Samoilov et al demonstrate that LFAO exposure in the area of non-formed wave cannot be correctly assessed without accounting to the phasic shift between sound pressure and oscillation movement of air media particles, when considering aural perception.

The comparison of microphone response spectra for different frequency acoustic oscillations of similar power flux densities has revealed equipotential feature of basic harmonics of electric cochlear responses in the aural range. Non-linear cochlear contortions in case of LFAO exposure of power flux density of 1-100 $mW \cdot m^{-2}$ are insignificant. Coefficients of non-linear contortions of the microphone potentials were not significantly changed with the frequency increase. This finding confirms the leading role of the power flux density in the microphone cochlear response at low frequencies.

Thus, the comparison of obtained dependencies versus the dynamics of spatial distribution of acoustic stimulation parameters certifies to the fact that the microphone potential amplitude induced by low frequency acoustic oscillations is determined by the incoming power flux density in the aural system.

Aural sensitivity measurements were elaborated by N.I. Karpova et al (1981), which sensitivity was evaluated at minutes 10 and 15 of the infrasound exposure at 10 Hz and 135 dB. Obtained data certify to the specific infrasound sensitivity of aural organ. At minute 10, the clear decrease of aural sensitivity was recorded at all examined frequencies; the average decrease of 10-15 dB was found at low frequencies predominantly. When concerning audiograms recorded immediately after exposure, they were specific to almost

complete recovery at high frequencies and some recovery at middle and low frequencies (for 5-7 dB, in average). For instance, the audiogram (see Figure 23) indicates to the aural sensitivity decrease at 125-2000 Hz for 15-20 dB when measured at minute 10 with correspondent 5-10 dB recovery at all frequencies after the exposure termination.

When analyzing audiograms recorded after 15 minutes infrasound exposure, in the majority of cases the insignificant improvement of aural sensitivity was found at first minutes of the recovery period (Table 3.4).

Table 3.4 - Aural threshold change after infrasound exposure at 10 Hz and 135 dB (percentage of total changes)

Exposure moment	Aural change, dB	Frequency, Hz								
		125	250	500	1000	2000	3000	4000	6000	8300
1st minute of recovery period	< -10	85	75	90	40	55	85	60	65	35
	unchanged	15	10	5	45	35	5	35	25	40
	< +10	0	15	5	15	10	10	5	10	25
30th minute of recovery period	< -10	25	30	10	10	35	40	50	15	15
	unchanged	55	45	85	60	50	40	10	65	60
	< +10	20	25	5	30	15	20	40	20	25

The provided data certify to the fact that < 10 dB aural threshold decrease is present. Most confident decrease of aural thresholds was found at 125, 250, 500, 3000 Hz. The lowest improvement of aural sensitivity has happened at 8000 Hz. The aural threshold increase at all frequencies was observed in insignificant percentage of cases and it was less than 5 dB (10 dB in a few cases), which was not statistically confident.

After infrasound exposure at 5 Hz and 135 dB, aural thresholds were unchanged in the majority of cases.

Studies elaborated for infrasound exposure at 5 Hz and 100 dB have not revealed aural sensitivity shifts.

H.E. von Gierke, C.W. Nixon (1976) report that pressure sensations have occurred in the case of the whole body infrasound exposure inside dynamic pressure chamber. The otological examination of examinees has revealed the vascular reaction of the tympanic membrane. It was correlated to the tympanic membrane inclination resulted from air pressure decrease in the middle ear cavity. Such decrease is resulted from the acoustic pressure "pushing out" the air from the middle ear via auditory tube. Besides, the inclination is resulted from middle ear muscular tension. The vascular injection of the tympanic membrane was more expressed for higher stimulation. In some conditions of tympanic membrane inclination and vascular injection, the pain has occurred.

According to G. Bekesy and H.E. von Gierke, pain thresholds are almost coincided. For 20 Hz the threshold is 140 dB and it is increased to 162 dB at 2 Hz. M.J. Evans and W. Tempest (1972) have

provided information about the middle ear pain for significantly lower levels affecting in the variable pressure chambers.

The infrasound effects in the internal ear system are important. L. Pimonow (1971) has supposed that very low frequency infrasound cannot reach the cochlea due to the pressure compensation in the auditory tube. However, D.E. Parker (1970) has demonstrated that infrasound energy is transmitted to the internal ear. He has recorded pre-lymph movement in the upper semicircle channel of exposed guinea pigs. According to G. Bekesy (1962), the intensive exposure at < 20 Hz has not induced major membrane inclination. Some researchers suppose that helicotrema can shunt the acoustic energy from the major membrane. The efficiency of this shunt is increased versus acoustic frequency decrease (Dallos P., 1973).

These data certify to the suggestion that internal ear does not react to the infrasound though acoustic energy penetrates to the internal ear. However, infrasound is aurally perceived without tone distinguishing.

In 1936, G. Bekesy has determined aural thresholds for the infrasound band and "audible" low frequency sounds (from 20 Hz to 100 Hz). The possibility of the perception of very intensive infrasound was also demonstrated by G.A. Brecher (1934); J.F. Corso (1958); A. Finckle (1961).

N.S. Yeowart et al, (1967); N.S. Yeowart, M.E. Bryan (1969); N.S. Yeowart, M.J. Evans (1974) have assessed aural thresholds at 1 Hz to 100 Hz applying specialized helmet to expose ears only as well as the variable pressure chamber to expose the whole body. The thorough analysis of the acoustic spectrum has demonstrated that even maximal level of the sound pressure results to harmonic contortion levels below the aural threshold for corresponding frequencies.

N.S. Yeowart has determined the frequency border of ~ 18 Hz below which tones are not distinguished. He describes subjective perception of the infrasound as follows: at 5 Hz to 15 Hz the infrasound is perceived as rough uneven sound and it is perceived as air whistle at < 5 Hz. These peculiarities are explained by the separate perception of oscillation cycle phases.

A number of studies was tried to evaluate the temporal shift (TS) of the aural threshold. Data provided by Table 3.5 are contradictory and their analysis does not assure the infrasound ability to induce TS.

J. Tonndorf (1950) has described unfavorable infrasound effects observed in German submariners found to have middle ear pathology. C.W. Nixon (1974) has noted that temporal shift was insignificant even in case of rather powerful harmonic contortions generated by the equipment in the aural band.

D.L. Johnson (1974) has got TS effect at 140 dB only. In case of 5 minute exposure, only 1 out of 8 examinees has been observed to

have TS. 30 minutes exposure data are difficult to discuss, because only one person was examined (Table 3.5).

Table 3.5 - Infrasound aural effects (Izmerov N.F. et al, 1998)

Study	Exposure parameters	Aural changes	Recovery
Tonndorf J., 1950.	Diesel submarines. 10-20 Hz. SPLs are not given.	Decrease of audible period of tuning fork sound	Several hours
Mohr G.C. et al., 1965.	Pure tones. 10-20 Hz noise. 150-154 dB. < 2 minutes.	No changes. TTS is absent at hour 1 after exposure	-
Jerger J. et al., 1966.	Sequential 3 min exposures of the whole body 7-12 Hz. 135 dB.	TTS at 3000-6000 Hz in 11 out of 19 examinees.	Several hours
Nixon C.W., 1973.	Pistophone connected to the ear via ear bush. 18 Hz. 135 dB. Series of 65 min exposures in rapid sequence.	TTS of 0 to 15 dB at minute 30 after 30 min exposure	30 min
Nixon C.W., 1973.	Pistophone connected to the ear via ear bush. 14 Hz. 140 dB. Six separate exposures of: 5, 10, 15, 20,25 and 30 min.	1st examinee - TTS is absent, 2nd examinee - insignificant TTS, 3rd examinee - TTS of 20-25 dB.	30 min
Johnson D.L., 1973.	Via ears only: pressure chamber connected to the flexible pipe and bush 171 dB (1-10 Hz) 26 s; 1 examinee 168dB (7Hz) 1 s; 1 examinee 155 dB (7 Hz) 5 s; 1 examinee 140 dB (4, 7, 12 Hz) _0 s; 1 examinee 140 dB (4, 7, 12 Hz) 5 s; 8 examinees 135 dB (0.6; 1.6; 2.9 Hz) 5 s; 12 examinees 126 dB (0.6; 1.6; 2.9 Hz) 16 s; 11 examinees	TTS is absent. TTS is absent. TTS is absent. TTS of 14-17 dB. TTS of 8 dB in 1 exam. TTS is absent.	30 min

Multiple exposures has resulted too more expressed changes of the middle ear cells (up to nuclei pectosis). Unfortunately, data on spectral composition are not provided.

Thus, provided data demonstrate that infrasound is able to induce middle ear changes and aural effects, however the middle ear damage is not proved. Thresholds of pain, tactile and aural sensations depend upon the frequency and increase with its decrease. Aural infrasound thresholds are 95-135 dB.

The examined perception thresholds at < 20 Hz (Bekesy G. von, 1936 et al) have demonstrated that clean tone perception is always observed at > 20 Hz near the aural threshold. If the frequency is decreased to 10 Hz, aural sensations are close to the tactile ones. If the intensity is elevated to ~ 140 dB, aural sensations are accompanied by clear tactile sensations. The perception threshold of 130 dB is specific to 1.5 Hz and ~100 dB is specific to 10 Hz (Tempest W., 1976).

G. Bekesy has demonstrated that normal ear perceives sound oscillations of very wide frequency range of ~ 0 Hz to 40-50 kHz at

correspondent intensity of these oscillations. Thus, if sound pressure exceeds known lower aural threshold, the aural system and cerebral aural center are able to perceive and analyze not only acoustic sounds but infrasound as well.

L. Pimonow (1971) indicates that infrasound oscillations are not perceived by the spectral analyzer of the aural organ, so they do not induce the tine sensation, but these oscillations can induce other sensations (pressure sensation, particularly) at the specific intensity level.

At present time, a number of issues regarding infrasound health effects in aural analyzer are unclear, however, it can be concluded that LFAO aural receptor responses are proportional to the power flux density. LFAO sensorial perception is determined by direct acoustic stimulation effects in the Corti's organ and is principally similar to the aural perception of audible sounds.

3.1.2 LFAO vestibular reception

The vestibular system is also LFAO sensitive. Acoustic oscillations of low frequencies and > 105 dB have induced body equilibrium disturbance, orientation loss, mild nausea and giddiness (Parker D.E. et al, 1968; Parker D.E., 1976; Suvorov G.A., 1983). In 85% of examinees have been found to have vertical nystagmus. M.J. Evans (1976) has determined frequency-threshold curves of nystagmus induced by LFAO and demonstrated that threshold sound pressure is 125 dB at 7 Hz; the frequency increase was specific to the threshold decrease for 5 $dB \cdot octave^{-1}$. The nystagmus incidence rate has not depended upon the frequency. M.J. Evans has also observed vertical nystagmus in laboratory animals.

In some experiments (Bergmann R., 1988), vestibular disturbances were not recorded even for high infrasound intensities, which could be related to different conditions of acoustic signal generation.

The involvement of labyrinth semicircle channels in the LFAO sensorial perception was confirmed by tests with surgical cut-off of pair VIII of cerebral cranial nerves in guinea pigs (Parker D.E., 1976). The labyrinth denervation has resulted to the disappearance of nystagmus and head movements in LFAO exposed animal. Vestibular responses to low frequency acoustic oscillations were absent in case of streptomycin administration to semicircle channels. At same conditions, the otolith mass extraction has resulted to significantly lower vestibular disturbances (Parker D.E., 1976).

LFAO efficiency in vestibular system is proved by cytomorphological examinations. Long term (more that 3 hours) exposure at 4-16 Hz octaval frequencies and 90-110 dB has induced mitochondria crest deformation and Holdgi complex cistern

enlargement in central cells (Nekhoroshev A.S., 1985; Pavlov V.V., 1991),

Authors think that aural and vestibular LFAO perception mechanisms are apparently similar. Changes of the pre-lymph pressure induced by acoustic stimulation are able to cause oscillations of membrane labyrinth of semicircle channels. The endo-lymph flow from labyrinth to endolymphatic sack can result to significant movement of cupolas with deformation of hairpin cell cilias and followed receptor potential generation (Trinus K.F., 1988; Dixa M.R., Hooda J.D., 1989). This eventual sequence is considered to be the initial point of the reflex reactions (Gierke H.E. von, 1976; Nixon C.W., Evans M.J., 1976; Parker D.E., 1976; Trinus K.F., 1988).

Thus, LFAO reception is participated by both aural and vestibular system.

A few publications devoted to functional state of vestibular analyzer in case of the infrasound exposure contain rather contradictory data. Apparently, it is explained by different infrasound generation techniques and methods for assessment of vestibular analyzer function.

In the USA, infrasound effects in human (including vestibular analyzer investigation) were tried in the framework of medical support of space flights to exclude super-critical loads in astronauts and auxiliary personnel at the space ship launch. These studies have applied short time exposure (several minutes) and high infrasound pressure.

Alternatively, European countries and Russia has investigated industrial and environmental infrasound. Loads are relatively low intensive and durations are longer.

Apollo program (Mohr G.C. et al, 1965) has involved the spatial orientation examination in case of human exposure to infrasound generated by load speaker placed inside resonator pipe. SPL was up to 154 dB. Finger-nasal test and target test were used as the criteria of the biological effect. Statistically significant infrasound effects were not found and authors have recognized the assessment methods to be rough and insufficient to record insignificant changes of spatial orientation.

B.R. Alford et al (1966) have observed people exposed to infrasound in dynamic pressure chamber (119 - 144 dB at < 22 Hz). Exposure time was 3 minutes. Vestibular analyzer state was determined by electronystagmography. Though vestibular analyzer function disturbances were found in 1 out of 21 examinees, authors have supposed that longer exposure would change vestibular analyzer state more significant if compared to all other physiological responses.

V. Gavreau et al (1966) have concluded that low infrasound levels have to affect vestibular analyzer and cause fatigue rapidly.

Vast study of vestibular analyzer in case of infrasound exposure was done by English researchers (Evans M.J., Tempest W., 1972).

Infrasound source was specialized headphones connected to low frequency generator of 1 Hz to 200 Hz working range. Maximal SPL was 146 dB. To record possible infrasound effect in vestibular analyzer function, electronystagmography was applied. Three types of exposure were used: monoaural, bi-aural phasic and bi-aural anti-phasic ones.

Preliminary observations have demonstrated that vestibular analyzer response as vertical nystagmus was more expressed for bi-aural anti-phasic exposure (85% of cases). That is why, the followed examinations were tried in this very mode of the exposure. Sound pressure levels were increased from 100 Hz to 145 dB with 5 dB steps. This SPL range was tried at 2, 4, 5, 7, 12, 15 and 20 Hz. Infrasound exposure was applied within 5 s to 85 s. each experiment has involved only one combination of time and intensity.

Series of infrasound exposure at 7 Hz were tried first. This frequency was chosen according to V. Gavreau (1966), who has indicated to most harmful effect of this frequency, which is close to the resonance frequencies of body organs and cerebral rhythm. Figure 3.14 demonstrates the dependence of the threshold level of vertical nystagmus versus duration of anti-phasic infrasound exposure. Similar series were tried at 2, 4, 5, 12, 15 and 20 Hz.

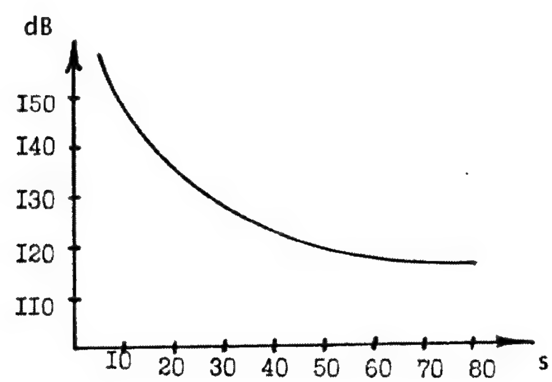


Figure 3.14 – Dependence of the threshold level of vertical nystagmus versus duration of anti-phasic infrasound exposure at 7 Hz (Evans M.J., Tempest W., 1972)

Figure 3.15 demonstrates dependence of SPL inducing nystagmus vs. stimulation duration. Thus, threshold curves of nystagmus reaction were obtained for a number of infrasound frequencies. These curves indicate that minimal SPL required to induce vertical nystagmus is decreased with frequency increase in case of anti-phasic infrasound exposure.

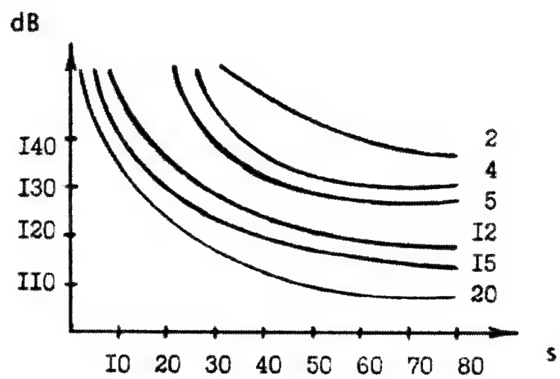


Figure 3.15 - Sound pressure threshold vs. stimulation duration at 2, 4, 5, 12, 15 and 20 Hz (Evans M.J., Tempest W., 1972)

Subjective reactions have included fatigue and strong feeling of tympanic membrane movement; some examinees have noted mild sensation of the falling forward. Basing upon obtained data, the conclusion was drawn that bi-aural anti-phasic infrasound exposure induces vestibular analyzer function disturbance. This disturbance consists in the vestibular analyzer function stimulation and vertical nystagmus occurrence.

Graham Chedd (1975) has provided data similar to these of Tempest. Same system of headphones and electronystagmography were used. The exposure was at 2 to 10 Hz and up to 160 dB. Data have confirmed vestibular function stimulation in case of the infrasound exposure. All examinees have felt mild nausea, rotation sensation, consensual rotation of eyeglobes and some discomfort. Authors do not indicate to the type of the infrasound exposure (phasic or anti-phasic one) and nystagmus direction (vertical, horizontal or rotating one).

M.J. Evans and W. Tempest studies were criticized by the American group leaded by H.E. von Girke. They have repeated M.J. Evans and W. Tempest experiments (Johnson D.L., 1973). Three examinees were exposed to anti-phasic exposure to 145 dB and 155 dB at 7 Hz. The nystagmus was not recorded nether for anti-phasic nor phasic exposure and for mono-aural exposure as well.

D.L. Johnson (I973) has examined infrasound effects in the equilibrium in rabbits. For very high SPL (up to 172 dB) the tympanic membrane rupture and middle ear muscle hemorrhages have occurred but equilibrium disorder was not found.

D.E. Parker et al (I973) have examined vestibular function in case of the exposure to 172 dB (1, 2 and 4 Hz); 169 dB (10 Hz) and 162 dB (20 Hz). Experiments were tried in guinea pigs and monkeys. Eye motility was assessed by electronystagmography. Any eye motions caused by vestibular analyzer irritation was not found in guinea pigs or monkeys. At the same time, the exposure to audible sound of I40–I45 dB (500 Hz) has induced clear nystagmus in monkeys.

The criteria of the functional state of the vestibular analyzer were the ability of volunteers to keep equilibrium on rails of different width. Infrasound exposure was both bilateral and unilateral. SPL has reached 155 dB, and exposure duration was 2 - 5 min at 0.6; 1.6; 2.4 and 7 Hz. Effects were not found. D.L. Johnson reports that he has been personally exposed to unilateral infrasound of 168 dB at 7 Hz within 1 minute and could keep equilibrium when standing on one foot. Nystagmus and vibration sensation was not felt; in case of audible sound exposure, disturbances have occurred since 95 dB and reached maximum at 140 dB.

The vestibular stimulation under infrasound exposure has been investigated by German researchers (Izing H. et al, 1981). This study has used anti-phasic stimulation of aural analyzer, according to Evans and Tempest. The electronystagmography was added by "Whittaker" optical system to record nystagmus. This system is able to detect sight direction changes very accurately (less than half of degree).

Applying headphones, 5 persons were exposed to 4, 5, 7, 10, 12, 15, 17 and 20 Hz with 135 dB. Exposure duration was 3 minutes. Besides, additional anti-phasic infrasound exposure was applied (130 dB and 140 dB) at 5 Hz to 12 Hz nystagmus was not found.

In Russia, volunteer tests to reveal infrasound effects in vestibular analyzer were tried by N.I. Karpova et al (1979). SPL was 135 dB at 5 Hz and 10 Hz. The electronystagmography method has not revealed vestibular function disturbances.

Thus, the literature references contain two opposite opinions regarding vestibular analyzer effects of the infrasound. M.J. Evans and W. Tempest (I972) have demonstrated possible vestibular stimulation by anti-phasic infrasound exposure. American researchers could not repeat these studies (Johnson D.L., 1973). Followed studies (Karpova N.I. et al, 1979; Izing H. et al, 1981; Parker D.E. et al, 1973) has not revealed any vestibular analyzer changes too.

When explaining results of M.J. Evans and W. Tempest, von H.E. Gierke and D.E. Parker (1976) suggest that vertical nystagmus is the

consequence of vestibular analyzer irritation with audible sound component. This audible component could be the contortion of the infrasound signal at generation. Besides, the absence of the control and placebo could result to wrong interpretation of nystagmograms.

Though the vestibular effect absence was demonstrated by the majority of studies, we think that the issue of vestibular analyzer state in case of the infrasound exposure is not solved finally. Firstly, major factual material has been obtained for the exposure of ears only (i.e. the exposure of the peripheral endpoint of aural analyzer), whereas real infrasound exposure occurs in the whole body. Secondly, the vestibular analyzer state assessment was done applying methods, which presumed vestibular activation and are directed to nystagmus direct detection. In such case, they have used methods for sensitivity and reactivity of the vestibular analyzer.

In 1980-1984, the Institute of Biophysics has investigated vestibular function state in laboratory animals and volunteers exposed to the infrasound (Gorshkov V.V., 1984).

To assess vestibular function, tests based upon the adequate irritation of cupolar apparatus of semicircle channels of labyrinth, when applying angular accelerations of exactly established magnitudes. The nystagmus response was recorded by electronystagmography and the quantitative assessment was done via nystagmus duration, number of nystagmus attacks and nystagmus incidence rate.

The new approach of this study has consisted in the application of physiological techniques to assess vestibular function (angular accelerations). Basing upon the pure quantitative results, the objective assessment of even insignificant changes of vestibular analyzer functions was available including both its stimulation and depression.

Experimental studies

Studies were tried in matured Chinchilla rabbits of 2.0-2.5 kg body weight.

Healthy rabbits were examined for vestibular analyzer state using sensitivity threshold and reactivity to the elevating stimulations (see below). It was established that most expressed individual differences are specific to the threshold of vestibular analyzer sensitivity. Animals were subdivided into 2 groups according to this index.

First group had sensitivity threshold of 0.85 $°/s^2$ to 1.15 $°/s^2$ and second group had the threshold of > 1,5 $°/s^2$. Besides, some animals have expressed labyrinth asymmetry. This asymmetry was confirmed by cupolagrams based upon vestibular analyzer reactivity data. According to literature references, sensitivity threshold of vestibular analyzer is ~ 1 $°/s^2$ in rabbits (Grigoriev Yu.G. et al, 1970), which corresponds to our data. Thus, only healthy rabbits with normal sensitivity threshold of the vestibular analyzer were involved in the study.

108 were examined including 80 test animals and 15 controls; other 13 rabbits were excluded from the study according to clinical indices or

sensitivity threshold of vestibular analyzer (high thresholds or expressed labyrinth asymmetry). Low sensitivity of the vestibular analyzer and labyrinth asymmetry found in some animals is obviously explained by the present bilateral or unilateral labyrinth pathology.

Volunteer examinations

18 male volunteers were involved (22 to 40 years ages). The distribution in experimental series in shown by Table 3.6.

Table 3.6 - Series of volunteer study

No.	Series title	Volunteer number	Observation number	Tests applied
1	Functional state of the vestibular analyzer in case of KDD infrasound exposure	12	15	Linear increase of acceleration (LIA test) and trapezoid test (see description in the text)
2	Functional state of the vestibular analyzer in case of formed acoustic field infrasound exposure	6	6	LIA test and trapezoid test

Infrasound sources

Infrasound sources are both dynamic pressure chambers and installation of formed acoustic infrasound field.

Dynamic pressure chambers (DPC) were of three types including two chambers for animals and one chamber for volunteers (DPC-1). Principal schemes are given by Chapter 2 above.

In case of the formed acoustic field the examinee was at the wavelength distance from the source; in our experiment (14 Hz) the distance was 24 meters. Such distance results to the relatively low SPL (130 dB). However, it should be underlined again, that this installation generates formed infrasound field, i.e. the infrasound existing in the human environment.

Methods

The functional state of the vestibular analyzer was examined before and after exposure. In rabbits, this assessment was done 7-10 minutes after the exposure and volunteers were examined 15-20 minutes after exposure. These time periods were constant in all experimental series of rabbits or volunteers.

The functional state of the vestibular analyzer, threshold SPL and frequency specificity were assessed both in experimental and control animals. SPLs and frequencies applied are shown by Table 3.7.

Each experimental "point" (frequency and SPL combination) was attributed by 5 rabbits. Control group (false exposure) was composed of 5 rabbits too. 60 rabbits were involved in the experiment, totally. The vestibular analyzer functional state assessment has included the threshold evaluations of the sensitivity and vestibular analyzer reactivity to elevating stimulation (trapezoid test).

The vestibular analyzer functional state in case of the rabbit exposure to high frequency sound with infrasound modulation was examined according the same principle scheme. The difference was the exposure time (5 minutes) and the absence of time intervals between functional tests and irradiation.

Table 3.7 - Frequencies and SPLs applied for experimental series on vestibular analyzer function, threshold SPL and frequency specificity of the infrasound effects

SPL, dB	Frequency, Hz		
	4	8	14
160	+		
150	+		
140	+	+	+
130	+	+	+
120	+	+	+

20 rabbits were involved including 10controls. Test rabbits were exposed to modulated sound of 103 dB intensity and 16000 Hz carrier frequency. The modulation frequency is 4 Hz. Control animals were exposed to the same sound but without modulation. Vestibular analyzer function was assessed via sensitivity threshold.

Observation schemes of volunteer vestibular analyzer function in case of DPC or formed acoustic field exposure were the same. The exposure time was 20 minutes. Inside DPC, the exposure parameters were 8 Hz and 150 dB. 12 volunteers were tested including three volunteers also examined three hours after the exposure.

Under the formed acoustic field conditions, 6 volunteers were irradiated to 4 Hz, 130 dB. Vestibular analyzer assessments were done via threshold evaluations of sensitivity and reactivity to stimulations.

Threshold evaluations of sensitivity and vestibular analyzer

The sensitivity threshold of the vestibular analyzer was assessed in the rotation system (RS-6 Rotation System, Sweden), this system contains rotation installation, computer controller and communication cables. The human chair and animal fixation are available in the rotation system.

The chair headrests have fixed the volunteer head in the mildly bent position (~ 30°). This position provides maximal adequate irritation of horizontal semicircle channels of the vestibular analyzer in case of the horizontal plane rotation. The rotation axis has crossed the head.

Rabbits were in the "crucified" position during the rotation. Animal head was fixed. The rotation axis has crossed the animal head. All vestibular tests were done under conditions excluding sound and light irritations.

RS-6 rotation system provided the angular acceleration, which is the adequate irritation of the vestibular analyzer in the wide range of magnitudes. To determine the sensitivity threshold, the specialized test of linear increase of the acceleration (LIA test) is presumed. At this mode, the system gradually increases the acceleration with the increase at each second. For human this increase was 0,025 $°/s^2$, and for rabbit it was 0,05 $°/s^2$. Such acceleration increase ("accelerated acceleration") is presumed by the controller.

When the angular acceleration has reached the threshold value, nystagmus reaction has occurred. After some exceeding the threshold, the system changes to the uniform rotation mode. Since Mach (1875), the passive uniform rotation does not irritate vestibular analyzer because of the angular acceleration absence. During the uniform rotation, the mitigation of all vestibular reactions is present. According to literature (Grigoriev Yu.G., 1967; Grigoriev Yu.G. et al, 1970), this mitigation occurs at minutes 1-1.5.

LIA test applies insignificant sub-threshold irritations, so we had uniform rotation within 1 minute. After the uniform rotation, the system was slowly stopped. This phase was done similarly to the acceleration i.e. negative acceleration decreased at each second was applied until the full stop.

Thus, one rotation tour was specific to positive and negative angular accelerations, which has provided the information regarding threshold of the left and right labyrinth. When evaluating sensitivity threshold, we have done 4 rotation tours with 1-1.5 minute interval and data were averaged.

Nystagmus reactions were recorded applying electronystagmography (Minkovsky A.Kh. et al, 1966; Grigoriev Yu.G. et al, 1970; Palchuk V.T. et al, 1981). Leads were placed bitemporally at outer eye areas. In rabbit experiments, needle leads were pinned at outer eye areas. Obtained biopotentials were transmitted via current conducting rings and cables to EEG recorder (E84 model, Italy) with time constant of 1.0. Nystagmograms were recorded at paper band velocity of 7.5 mm/s (rabbits) and 15 mm/s (volunteers). Higher paper band velocity and lower magnitude of each second acceleration increase in humans versus rabbits were selected to increase the accuracy of sensitivity thresholds. At normal conditions, the sensitivity of the human vestibular analyzer is ~ 3 folds lower than that in rabbits (0.3 $^{0}/s^{2}$ in human versus 1 $^{\circ}/s^{2}$ in rabbit). Therefore, in case of low recording velocity and relatively high acceleration increase, the first nystagmus attack in human would be too close to the rotation start-up point. The angular acceleration was determined as the product of time since rotation start-up to the time of first nystagmus (in seconds per acceleration increase per second).

Vestibular analyzer reactivity

The vestibular analyzer reactions to sub-threshold increasing adequate stimulation were also assessed applying RS-6 rotation system. Trapezoid test was used. During this test, the rotation system starts the rotation with constant acceleration (5.0 $^{\circ}/s^{2}$ in all tests).

At the specified angular velocity, the system was automatically re-switched to the uniform rotation within 1-1.5 minutes. Thereafter, the stopping was initiated with negative angular acceleration of 100 $^{\circ}/s^{2}$. Nystagmus reactions have occurred at the acceleration period. Nystagmus recording was done applying electronystagmography.

The rotation system has reached following angular velocities: 15, 30, 60 and 90 $^{\circ}/s^{2}$. Followed velocity increase is inconvenient because such strong stop stimulation results to the "force law" rule violation and response is not proportional to the stimulation.

The trapezoid test for each angular velocity was done twice applying left and right rotations. Time interval between rotations was 2 minutes.

Nystagmograms were assessed via nystagmus reaction time, number of nystagmus attacks and nystagmus incidence rate. Each of these parameters was accompanied by cupolagram reflecting dependence of the stimulation magnitude versus response. Cupolagrams are based upon the regulation discovered by Egmond, Groen and Jongkees (l949), which demonstrates that the vestibular analyzer response value is proportional to logarithm of the stop stimulation value.

The obtained results were statistically analyzed applying non-parametric difference criteria. Non-paired variants were applied by U-criterion of Wilcoxon-Mann-Whitney and paired variants were applied by T-criterion of Wilcoxon. After the normality test via asymmetry and excess of the

distribution, t-criterion of Student was applied for paired and non-paired variants. The differences were confident if p>95%.

Experiment results for threshold level and frequency ratio of infrasound vestibular analyzer effects in rabbits

Study results have revealed the vestibular analyzer function effects in rabbits. These effects consist in the decreased sensitivity and reactivity of vestibular analyzer.

Data for examined SPL values at 4 Hz are given by Table 3.8.

Table 3.8 - Threshold changes for vestibular analyzer sensitivity after 30 min exposure at 4 Hz

SPL (dB)	Averaged group threshold (°/s²)		Confidence
	Before exposure	After exposure	
160	1.09±0.44	1.54±0.54	Confident with _<0.01
150	0.96±0.17	1.38±0.47	Confident with _<0.01
140	1.16±0.14	1.27±0.09	Unconfident
130	1.00±0.19	1.10±0.21	Unconfident
120	1.04±0.19	1.06±0.12	Unconfident

Confident changes after 30 min exposure at 4 Hz were found for SPL of 160 dB and 150 dB. The individual statistical analysis of data for each of 5 rabbits for each group)40 observations totally) has revealed similar changes. Applying U-criterion of Wilcoxon-Mann-Whitney, the confident differences of thresholds before and after exposure were found in all rabbits for SPL of 160 dB and 150 dB. However, it should be noted that individual statistical analysis has revealed differences in two rabbits of group exposed to 140 dB.

Generally, Table 3.8 indicates that statistically significant changes were not found. Individual analysis of sensitivity thresholds before and after the exposure of < 140 dB has not revealed differences in any rabbit. Table 3.9 demonstrates that statistically confident differences were noted for 140 dB exposure within 30 min at 8 Hz.

Table 3.9 - Threshold changes for vestibular analyzer sensitivity after 30 min exposure at 8 Hz

SPL, dB	Averaged threshold in groups M±m, °/s²		Confidence
	Before exposure	After exposure	
140	1.06±0.23	1.26±0.28	Confident with p<0.01
130	1.10±0.16	1.14±0.17	Unconfident
120	1.16±0.20	1.12±0.21	Unconfident

The individual analysis of sensitivity thresholds in this group has found confident changes in 4 out of 5 rabbits. Two rabbits had

confident changes for 130 dB. Rabbit group exposed to 120 dB was not found to have changes in any animal.

The sensitivity threshold of the vestibular analyzer in case of rabbit exposure to 140, 130 and 120 dB at 14 Hz is shown by Table 3.10.

Table 3.10 - Threshold changes for vestibular analyzer sensitivity after 30 min exposure at 14 Hz

SPL, dB	Averaged threshold in groups M±m, °/s²		Confidence
	Before exposure	After exposure	
140	1.0±0.13	1.18±0.05	Confident with p<0.01
130	0.92±0.07	1.13±0.07	Confident with p<0.01
120	1.09±0.22	1.12±0.23	Unconfident

Confident changes were found for 140 and 130 dB. Individual analysis has demonstrated that 5 rabbits (140 dB) and 4 rabbits (130 dB) have had changes. 120 dB group was not found to have confident changes in any rabbit.

To exclude uncertainty resulted from threshold changes induced by the rotation test itself, false exposure was tried in the control group (5 rabbits, 40 observations). False exposure results are shown by Table 3.11.

Table 3.11 - Threshold values for vestibular analyzer sensitivity before and after false exposure (control series)

Rabbit No.	Averaged threshold sensitivity M±m, °/c²		Confidence
1	0.97±0.22	1.08±0.29	Unconfident
2	1.33±0.13	1.26±0.30	Unconfident
3	1.28±0.30	1.28±0.20	Unconfident
4	1.23±0.24	1.39±0.43	Unconfident
5	0.78±0.33	1.07±0.49	Unconfident
In the whole group	1.12±0.26	1.22±0.16	Unconfident

This Table indicates that confident differences were not found in any false exposed rabbit. Similar results were obtained for group analysis.

The vestibular analyzer reactivity examination in rabbits exposed to elevating stimulation has revealed vestibular function changes similarly to the sensitivity examinations. These changes are the decrease of the nystagmus reaction time, nystagmus eye motility decrease and nystagmus incidence rate decrease after infrasound exposure if compared to initial data.

The statistical analysis of data on vestibular analyzer reactivity in rabbits has not revealed confident differences for any case.

Vestibular function assessments in human exposed to DPC infrasound

This study has revealed the vestibular analyzer reaction including the vestibular analyzer sensitivity threshold increase and the reactivity decrease trend. The threshold sensitivity data are given by Table 3.12

Table 3.12 - Average sensitivity threshold in 12 volunteers before and after exposure to 150 dB at 8 Hz

Reg. No.	Average sensitivity threshold M±m, °/s²		Confidence
	before	after	
1	0.24±0.06	0.58±0.09	Confident with p>99%
2	0.22±0.07	0.48±0.07	- " -
3	0.32±0.09	0.55±0.07	- " -
4	0.36±0.04	0.55±0.08	- " -
5	0.32±0.04	0.49±0.08	- " -
6	0.34±0.04	0.55±0.16	- " -
7	0.28±0.09	0.53±0.07	- " -
8	0.29±0.05	0.42±0.09	- " -
9	0.40±0.04	0.61±0.08	- " -
10	0.34±0.07	0.63±0.07	- " -
11	0.28±0.04	0.76±0.19	- " -
12	0.31±0.07	0.65±0.11	- " -
In the whole group	0.31±0.03	0.57±0.06	Confident with p>99%

The statistically confident increase of the threshold was found in all volunteers (p>99%). The group statistical analysis has found the confident threshold increases too (p>99%).

To assess the threshold sensitivity after the exposure, three volunteers were examined one after the exposure. Data are shown Table 3.13.

Table 3.13

Reg. No.	Average sensitivity threshold M±m, °/s²			Confidence
	before	after	at 1 h after	
1	0.34±0.07	0.63±0.07	0.54±0.07	Confident with p>99%
2	0.28±0.04	0.76±0.19	0.54±0.05	Confident with p>99%
3	0.31±0.07	0.65±0.11	0.43±0.11	Confident with p>99%

Thus, the statistically confident decrease of the vestibular analyzer sensitivity was noted in all three examinees at 1 h after the exposure if compared to the initial level.

The vestibular analyzer reactivity before and after infrasound exposure has been found to have the statistically unconfident trend to the decrease of nystagmus reaction time, nystagmus eye motility decrease and nystagmus incidence decrease.

The vestibular function assessment in humans exposed to formed infrasound acoustic field

6 observations were obtained in volunteers. The vestibular function before and after exposure to formed infrasound field of 130 dB, 14 Hz and exposure time of 20 minutes was assessed via sensitivity threshold and reactivity.

The confident change of vestibular analyzer sensitivity (20 min human exposure to 130 dB at 14 Hz) was not found.

The vestibular analyzer reactivity was not found to be confidently changed too.

Generally, one can conclude that vestibular analyzer response to the infrasound exposure consists in the functional inhibition. This inhibition is manifested via increased sensitivity threshold and decrease trend of vestibular analyzer reactivity.

The results of the infrasound exposure in rabbits have demonstrated that the functional decrease of vestibular analyzer activity depends upon the intensity and frequency of the infrasound. Most expressed vestibular analyzer function disturbances have occurred in case of maximal SPLs of the rabbit exposure. If SPL is decreased, the expressiveness of these disturbances has decreased and disappeared.

When comparing minimal SPL able to induce statistically significant differences of sensitivity thresholds before and after the irradiation at different frequencies (Figure 3.16), the clear regularity was found as follows: in case of the frequency increase the infrasound pressure threshold is decreased.

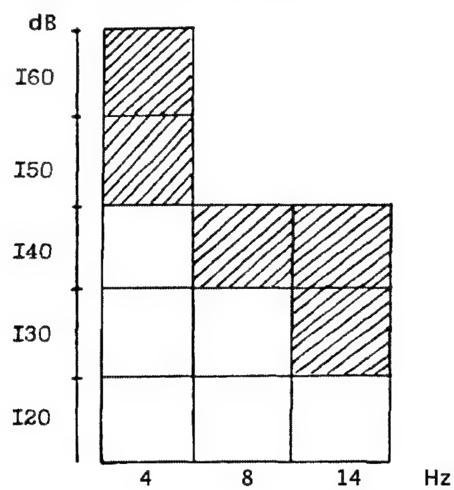


Figure 3.16 – Threshold sound pressure vs. Infrasound frequency
Hatched squares indicate to the presence of confident changes of sensitivity thresholds, non-hatched squares indicate to the unconfident changes

The minimal SPL required to induce the confident vestibular function inhibition is equal to 150 dB (4 Hz), 140 dB (8 Hz), and 130 dB (14 Hz). Thus, the clear frequency ratio is found for vestibular analyzer effects. The increase of the infrasound effect correlated to the stimulating frequency increase is obviously explained by the increase of the pressure oscillation frequency within the same period of time, i.e. the acoustic energy amount is increased.

As it was noted before, the individual analysis of rabbit data has revealed confident differences of sensitivity thresholds obtained before and after the infrasound exposure in groups of the exposure level below the threshold one. At 4 Hz, such differences were found in 2 out of 5 rabbits exposed to 140 dB; at 8 Hz, the same incidence was noted for 130 dB. The presence of such changes, apparently, indicates to separate animal beings, which are more sensible to the infrasound than the whole population. Perhaps, there are animals, which infrasound sensitivity is less than that in the majority of others. It is confirmed by the absence of statistically confident differences of sensitivity thresholds for two rabbits from groups of the threshold SPLs (140 dB and 8 Hz; 130 dB and 14 Hz).

When analyzing vestibular analyzer reactivity in rabbits, confident differences were not found. However, the vestibular analyzer reactivity was found to have the decrease trend. Cupolagrams obtained after the exposure to sub-threshold SPLs, have lower slope and nystagmus characteristics are lower, if compared to initial ones. Probably, the absence of confident reactivity changes (alternatively to sensitivity changes) can be explained by the fact that applied infrasound levels yet have not induce significant disturbances of the vestibular analyzer reactivity, or they are compensated by the supreme regulation.

The volunteer observations in the infrasound DPC exposure to 150 dB at 8 Hz have demonstrated the results similar to that in rabbits. All examined volunteers were noted to have the expressed vestibular analyzer sensitivity decrease. The sensitivity threshold increase in some examinees was more than 2 times higher than initial values, which, apparently, indicates to more expressed disturbances of vestibular analyzer function in human if compared to rabbits (the exposure conditions are comparable).

The statistical analysis of vestibular analyzer reactivity data on volunteers has not reveal confident differences between indices before and after the exposure. However, cupolagrams drawn on averaged characteristics of nystagmus reactions for the whole examinee group certify to the depression trend of vestibular function. Cupolagrams obtained after the irradiation are specific to lower slope and lower values of duration, rate and nystagmus eye motility, which is similar to rabbit findings. The causes of the confident changes are similar to that described for rabbits.

The repeated vestibular analyzer sensitivity examination in three volunteers tried one hour after the exposure termination has demonstrated that vestibular function disturbances have persisted. The statistical analysis of these data has revealed confident differences against initial sensitivity thresholds for each examinee and for the whole group ($p < 0.01$).

Volunteers exposed to formed acoustic field of 130 dB at 14 Hz were not found to have significant changes of the vestibular function. As it was noted above, the rabbits exposed inside the DPC have been found to have the confident threshold increase. This inconvenience, apparently, is explained by the fact that volunteers exposure was shorter (20 minutes despite of 30).

Thus, it can be concluded that the early vestibular analyzer response to the acute infrasound exposure consists in the functional activity decrease. This decrease is specific to the confident increase of the sensitivity threshold and to the decrease trend of vestibular analyzer reactivity, which was found in human and rabbits. The expressiveness of these changes depends on the intensity and frequency of the infrasound.

When comparing our data to available literature references, it should be noted that the decrease of functional activity of the vestibular analyzer is not noted anywhere. Different researchers have found the vestibular function stimulation (Evans M.J., Tempest W., 1972; Doroshenko P.N., Stepchuk I.D., 1983) or complete absence of any effect in vestibular analyzer (Johnson D.L., 1973; Parker D.E. et al., 1973; Ising H. et al., 1980; Karpova N.I. et al, 1979). The vestibular function stimulation found by M.J. Evans and W. Tempest (1972) is probably caused by the high frequency sound which was present at the time of the infrasound generation. Obviously, the same cause explains vestibular analyzer stimulation found by P.N. Doroshenko and I.D. Stepchuk (1983), who have examined this analyzer in compressor workers. It is known that threshold SPL of the acute audible sound is <100 dB (Johnson D.L., 1973). Obviously, in case of chronic exposure, lower levels of audible sounds can disturb functional status of the vestibular analyzer. However, it should be underlined that this study provides chronic infrasound data. Apparently, the long term infrasound exposure can induce different effects than the acute one.

The absence of the vestibular analyzer response to the infrasound exposure noted by authors named above can be probably explained by the different technique of the study. These studies have used direct electronystagmography, which can record only vestibular analyzer stimulation able to induce nystagmus. It was supposed that infrasound is the inadequate irritator of the vestibular analyzer, which is similar to the audible sound.

Basing upon our data, the mechanism of functional activity decrease response to the infrasound exposure can be suggested. Previously proposed vestibular mechanism (Parker et al, 1968;

Reschke and Parker, 1970) is unable to explain effects obtained by our study. This mechanism explains vestibular analyzer stimulation found for the static pressure increase in the exterior aural system of animals. According to these authors, the obtained vestibular analyzer stimulation has occurred due to the shift of the semicircle channels cupola affected by endo-lymph flux, which is originated from the stirrup movements in the oval window of the labyrinth. Reschke and Parker (l970) have disseminated their results to vestibular effects of the audible sound and supposed the same mechanism for the infrasound vestibular stimulation. However, followed studies have not demonstrated any vestibular analyzer responses to the infrasound oscillations.

When analyzing our studies, it is difficult to suppose that the vestibular analyzer function activity decrease is induced by some mechanical processes in cupola - endo-lymph system. The function decrease persisted in volunteers within 1 hour after the exposure termination completely excludes such option. It seems that infrasound vestibular analyzer effect is realized in receptor cells of cupolar apparatus or in supreme compartments of the nervous system (cortex compartment of the vestibular analyzer).

The available literature does not contain references to receptor cells of the cupolar apparatus in case of the infrasound exposure, however, there are detailed data regarding receptor cells of the spiral organ, which are of the same phylogenesis. V.N. Erokhin (1976) indicates to the fact that morphological changes of the content and distribution of nucleotide acids (DNA and RNA) in receptor cells of the cochlea were noted for 135 dB (15 Hz) exposure within 30 minutes. These changes can disturb cellular functions. It is possible, that such changes occur in receptor cells of semicircle channels.

It was already noted above that large number of publications devoted to different CNS compartments in case of the infrasound exposure exists (Karpova N.I., Malyshev E.N., 1981; Pimonow L., 1976; Tempest W., 1976 et al). These studies provide different data indicating to CNS function decrease response to the infrasound exposure. Thus, the decrease of the sensitivity and reactivity obtained in our study is not the infrasound effect in the vestibular analyzer. Apparently, these changes reflect function disturbances in central compartments of the nervous system and brain cortex, which are infrasound induced. In such case, the examination of the vestibular analyzer function indirectly assesses these disturbances and can be the criterion for the hygienic regulation of permissible infrasound levels.

The conclusions of the present study are as follows:

1. The DPC infrasound exposure in human and laboratory animals (rabbits) has induced the change of the vestibular analyzer function expressed by the sensitivity threshold increase and reactivity decrease trend.

2. The vestibular analyzer function decrease expressiveness depends upon the sound pressure. Since specific infrasound pressure level (> 130 dB) the sensitivity threshold is increased proportionally and the vestibular analyzer reactivity decrease trend is enforced.

3. Minimal (threshold) level of the sound pressure, which is necessary to get the confident depression of the vestibular analyzer function depends upon the infrasound frequency. If the infrasound frequency is increased, the threshold sound pressure is decreased: 150 dB (4 Hz), 140 dB (8 Hz) and 130 dB (14 Hz).

LFAO vestibular reception research in Labor Hygiene Institute of Russian Academy of Medical Sciences

Experimental studies of infrasound effects in vestibular and aural function were leaded by N.F. Izmerov.

The vestibular analyzer function was assessed applying the technique of Coriolis acceleration continuous accumulation (CACA). The adequate irritation of semicircle channels is the angular acceleration of the head in the channel plane. The transformation of mechanical force into the electric signal is produced at the surface of hairpin cells containing cupola. The utricles provides the information on the head position relatively to the gravity force. Sacculus is suggested to be responsible for signalizing the low frequency vibrations and non-linear accelerations; its function is close to the cochlea function but its structure is similar to the utricle one. The cupola shift is induced by any stimulation resulting to endo-lymph movement. The cupola shift was obtained applying angular acceleration, hydro-mechanical pressure and temperature. Vestibular nuclei of myelencephalon are the first CNS level, where the information provided by labyrinth receptors is processed. Vestibular nuclei are connected to different CNS compartments, to provide labyrinth monitoring and control of the effector reactions classificated by K.L. Khilov (1969) into somatic, vegetative and sensorial ones.

The semicircle channel irritation can occur in case of the uniform rotation, if the angular movement in the rotation plane is present. In such conditions, the Coriolis acceleration is present.

The rotation test for the tolerance of continuous accumulation of Coriolis acceleration was tried at portable electrically rotated chair according to S.S. Markaryan et al technique 1966); 180 degrees/s rotation with rhythmic tangential head shifts from the right to the left shoulder. CACA tolerance time was the criterion for vegetative reaction onset (Khilov K.L. (1969). Vestibular vegetative reactions have four expression grades: grade 0 - vegetative reaction absence; grade I - nausea sensation occurrence; grade II - nausea, hyperhydrosis, paling or hyperemia; grade III - grade II symptoms combined with vomiting. CACA tolerance time is assessed via grade

I and II reactions onset. At normal conditions, these periods are 15 min (grade O) and 5-10 min (grade I). In abnormal conditions, these periods are 10-5 min (grade II) and 5-2 min (grade III).

Static kinetic reactions were examined applying stabilography platform. The averaged quadratic means of the oscillation amplitudes of human body (closed eyes) were measured.

Vegetative reactions were examined applying ECG, pneumography and photoplethysmography. Subjective reactions were recorded at the infrasound exposure time and during CACA test.

CNS reactions were examined applying critical rate of flash coalescence (CRFC) neurodynamics index, Shulte-Gorbov psychological tests and entangled lines technique. CRFC was recorded from right and left eye and the measured parameter was the average rate of the light flashes (f, Hz), which is the index of functional eye asymmetry (AJ) correlated to functional inter-hemispheric asymmetry.

Studies were tried in healthy males of 20 - 30 years ages. 4, 8 and 16 Hz infrasound was applied aurally via electrodynamic system; 2 Hz exposure was elaborated applying piston system with the infrasound transmission to the chamber. Experimental infrasound parameters are as follows: 16 Hz (123 dB), 8 Hz (126 dB0, 4 Hz (129 dB0, 2 Hz (132 dB), which corresponds to Paris Colloquium curve (1973) based upon the similar energy level principle, which level excess was supposed to be harmful.

30 min exposure of human sitting in the chamber at rest has demonstrated the increase of the projected gravity center oscillation amplitude i.e. the decrease of the static kinetic stability most frequently manifested in the frontal plane, moderate decrease of the CNS activation and pulse rate decrease trend.

The examination of some functional parameters of the organism after the rotation CACA test has demonstrated both the decrease and the increase of the static kinetic posture regulation. However, the quality of the frontal regulation has worsened for 2 times more than sagittal regulation (i.e. static kinetic stability has worsen); the increase/decrease of the pulse rate was found as well as expressed CNS activation decrease.

Four experimental series have included 20 baseline tests and 40 experimental tests of the vestibular analyzer function, 160 examinations of aural sensitivity thresholds in the right and left ear, 320 otoscopy examinations and 160 examinations of the arterial pressure and pulse rate.

The vestibular stability decrease was noted for all infrasound frequencies. Maximal decrease (55%) was found at 2 Hz for 134 dB. If the baseline CACA tolerance time was 56 minutes and 30 seconds, this time has decreased to 25 minutes and 30 seconds after the exposure. Similar decrease of vestibular stability was observed at 4 Hz (for 54.3% - from 66 minutes and 55 seconds to

30 minutes and 35 seconds). Less expressed vestibular analyzer response was noted at 8 Hz: CACA tolerance time decrease was 34% (from 86 minutes and 35 seconds to 57 minutes and 5 seconds). 16 Hz infrasound exposure of 123 dB has insignificantly affected the vestibular analyzer (from 62 minutes and 25 seconds to 50 minutes and 20 seconds) (Table 3.14).

Table 3.14 – The expressiveness of vestibular, aural and subjective reactions after infrasound exposure

Infrasound parameters	Decrease of vestibular stability, % (on CACA tolerance time)	Subjective sensation incidence, %	Increase of aural sensitivity thresholds, %	Otoscopy change incidence, %
16 Hz, 123 dB	19.4	0	66.0	37.5
8 Hz, 126 dB	34.1	20.0	87.0	22.5
4 Hz, 129 dB	54.3	30.0	14.0	7.5
2 Hz, 134 dB (dynamic pressure chamber)	54.9	70.0	5.0	2.5
4 Hz, 129 dB (dynamic pressure chamber)	43.3	64.3	9.0	10.7

Similar changes were noted for subjective sensation incidences (discomfort, giddiness, nausea etc). Most frequent complains were found at 2 Hz: 14 out of 20 cases (70%); 6 out of 20 cases (30%) at 4 Hz, 4 cases (20%) at 8 Hz; complains were absent at 16 Hz. It should be noted that at 4, 8 and 16 Hz (aurally transmitted infrasound), subjective sensations have included discomfort, giddiness and rare nausea. In case of the dynamic pressure chamber at 2 and 4 Hz, subjective reactions were more variable. Almost all examinees have felt tympanic membrane shifts and ear coated sensations.

Significant portion of examinees has complained to transient fever, "movements" in the intestine and stomach, chest and temple pains. Complains to headaches, eye pain, sleepiness, anxiety, small change of the breath rhythm, occipital gravity, transient palate and face stiffness, increased salivation and increased saliva viscosity.

The character of vestibular vegetative reactions at the time of Coriolis acceleration after the infrasound exposure is interesting. Strong and subitaneous skin paling, hyperhydrosis, nausea and vomiting desires have occurred at the CACA test time in case of the exposure at 2 Hz and 4 Hz. At 8 Hz and 16 Hz, the Coriolis acceleration induced vestibular vegetative reactions were less expressed and have developed gradually.

The analysis of aural threshold changes has revealed different expressiveness of aural analyzer response to different frequencies. At 16 Hz, the confident aural threshold increase for 5–10 dB was noted when measured at audiometry frequencies of 500–8,000 Hz. At 8 Hz, the confident increase was noted when measured at

audiometry frequencies of 125–8,000 Hz. At 2 Hz and 4 Hz significant aural sensitivity threshold changes were not found.

According to otoscopy, changes of tympanic membrane were found (hyperemia of upper compartments and hammer handle). These changes were noted in 15 out of 40 cases (37%) after the exposure at 16 Hz; in 9 out of 40 cases (22.5%) at 8 Hz; in 3 out of 40 cases (7.5%) at 4 Hz, and in 2.5% at 2 Hz.

The frequency ratio of vestibular and aural analyzer responses have to be noted that lowest decrease of vestibular stability (19.4%) was found at 16 Hz as well as the absence of complainers; the aural sensitivity thresholds were confidently increased for 5–10 dB in the range of middle and high frequencies; in 37.5% of cases, otoscopy changes were found. At 2 Hz, highest decrease of the vestibular stability (55%) and expressed subjective reactions (70% of cases) were noted whereas the aural sensitivity thresholds were not significantly changed.

The comparative AP assessment has demonstrated confident decrease of maximal pressure ($p<0.05$) at 4 Hz (118.5 mm versus 111.6 mm) (Table 3.16).

Table 3.16 – Arterial pressure changes after the infrasound exposure

Infrasound parameters	No. of examinations	Arterial pressure (mm)		
		maximal	minimal	pulsed
16 Hz, 123 dB	20 20	116.3±1.56 113.5±1.66	63.90±1.97 64._5±2.32	52.35±2.30 48.80±2.48
8 Hz, 126 dB	20 20	119.4±2.40 113.5±1.95	74.9±2.11 72.7±2.06	45.25±1.61 41.45±1.57
4 Hz, 129 dB	20 20	118.5±2.31* 111.6 ±1.91	66.9±2.19 70.7±1.65	51.6011.84* 40.90±1.72
2 Hz, 134dB (dynamic pressure chamber)	20 20	116.4±2.08 114.6±2.33	68.5±7.33 70.0±1.73	47.95±2.24 44.50±1.95
4 Hz, 129 dB (dynamic pressure chamber)	14 14	117.14±2.12 114.93±2.00	66.79±2.92 70.57±2.12	50.40±2.61 44.40±1.68

Note: before/after the infrasound exposure; * - confident changes ($p < 0.05$)

The minimal AP had the increase trend at 2,Hz 4 Hz and 16 Hz, excluding 8 Hz, when the insignificant decrease was noted. The pulsed AP has decreased in all experimental series with maximal expressiveness at 4 Hz (51.6 versus 41 mm, $p<0.05$).

The decrease of pulse rate was observed at all examined infrasound frequencies. The reaction expressiveness was decreased for lower frequencies from 16 Hz to 4 Hz; at 2 Hz the strong pulse rate decrease was recorded. Apparently, the last is related to different way of the infrasound generation (dynamic pressure chamber).

Thus, the decrease of maximal and pulsed AP and pulse rate was found for all examined infrasound frequencies.

The vegetative index assessment has demonstrated that infrasound has induced parasympathotonia, which is increased with

the frequency decrease and most expressed for dynamic pressure chamber exposure.

At 16 Hz, the vegetative index before and after the infrasound exposure was ±11.9% and ±0,7%, respectively, whereas, it was +6.4% and -12.2% at 2 Hz.

The highest decrease of CRFC index was noted at 16 Hz. For decreased frequencies, the reaction expressiveness has decreased, however, it was confidently decreased at 16, 8 and 4 Hz.

The correlative regression analysis has revealed negative confident correlation of the infrasound versus vestibular stability, subjective sensation incidence and positive frequency correlation versus otoscopy change incidence and CRFC ($p<0.005$).

The relationship of the infrasound frequency (X, Hz) versus vestibular stability decrease (Y, %) is specific to the regression equation of: $Y = 60.9 - 2.7 X$, which can be applied to predict vestibular stability decrease versus the affecting infrasound frequency (Figure 3.17).

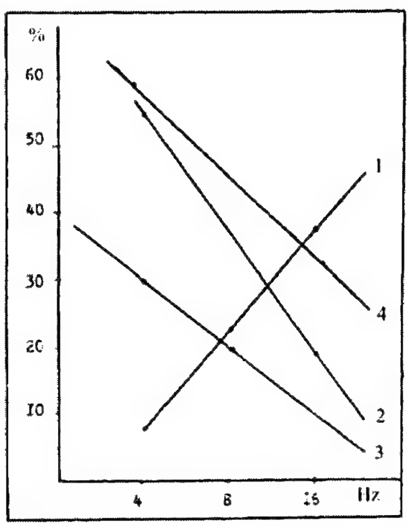


Figure 3.17 - The rate of effector human reactions after the cochlear vestibular analyzer exposure to 4 Hz - 129 dB, 8 Hz - 126 dB, 16 Hz - 123 dB (Izmerov N.F. et al, 1998)
1 - hyperemia of hammer and tympanic membrane; 2 - decrease of the vestibular stability (CACA test); 3 - subjective sensations (giddiness, nausea, discomfort); 4 - CNS activation decrease

Thus, Labor Medicine Institute studies have demonstrated the frequency ratio for physiological infrasound reaction expressiveness. If the infrasound frequency is decreased, the decrease of vestibular stability and more expressed vestibular

vegetative reactions were found; in the infrasound frequency is increased, otoscopy changes and confident aural threshold increase were found.

Generally, despite of some differences and contradictions of data obtained by both Russian and foreign researchers, the investigation of LFAO effects in the vestibular analyzer function can be the non-specific criterion for hygienic standardization.

3.1.3 LFAO sensorial perception of skin mechanical receptors

Other mechanical sensorial systems were supposed to perceive LFAO because of pressure and vibration sensations (Krylov Yu.V. et al, 1968; Andreeva-Galanina E.Tc. et al, 1970; Nishimura K. et al, 1987; Mungerl B.L., Ide C., 1988; Paranko N.M., Madatova R.B., 1990).

In 1980th experimental evidences of somatic sensorial perception of LFAO have occurred. Mutant mice experiments (non-sensible cochlea) at 6-50 Hz and 106-118 dB have shown 11-58% decrease of the swimming time versus control (Busnel R.G., Lehman A.G., 1978). B.K. Taylor et al (1991) have observed the orientation reaction in rats with extracted tympanic membrane. Explanations of changes found were referred to somatic sensorial systems.

B.L. Munger and C. Ide (1987) have revealed somatic sensorial sensitivity change after LFAO exposure at 128 and 256 Hz. The 10-15% increase of thresholds of vibration sensitivity of extremities was noted after LFAO exposure at 10 Hz and 135 dB (Alexeev S.V. et al, 1974).

The tactile sensitivity change in case of the exposure at 5 and 10 Hz was indirectly certified by the tone of peripheral vessels. Skin temperatures of upper extremities of examinees have decreased for 1.17°C and 0,64°C, respectively (Karpova N.I. et al, 1979). The somatic sensorial perception of 3-29 Hz oscillations has been confirmed by the revealed amplification of Δ- and Θ-rhythms in somatic sensorial cortical area (Bachurina T.N., 1974; Utemisov B.K., Nurbaev S.K., 1988). Besides, histomorphological changes of the rat brain in case of long term (> 3 hours) LFAO exposure at 8 Hz and 120-140 dB were noted as the separated neuron damage not only in aural but also in somatic sensorial cortical area (Nekhoroshev A.S., Glinchikov V.V., 1992). The chromatolysis and vacuole appearance in these neurons were found earlier in case of long term exposure to noise of 80-130 dB (Krivitckaya G.N., 1964; Nichkov S., Krivitckaya G.N., 1969; Korshunova V.I., 1976).

The literature references certify to the fact that only one experimental study was tried to examine Pacini bodies in cat mesentery (in vitro) after low frequency acoustic oscillations exposure (Mirkin A.S., 1966). The preparation was placed in the non-formed wave area. In case of the exposure at 60-400 Hz,

pulsed activity was found in the attached nervous fiber. The afferent pulsation was recorded for some acoustic frequencies and frequency threshold curve had several gaps and extremums. The maximal sensitivity of Pacini bodies was found at 100-120 Hz. Threshold sound pressure values at these frequencies were 3 times lower than at neighbor ones. Results indicate to the Pacini body ability to receive low frequency acoustic oscillations.

To reveal the role of mechanic receptor capsule for frequency selective perception of acoustic oscillations, the capsule was punctured. Such manipulation has resulted to strong increase of threshold sound pressure values and decrease of quality factor of frequency—threshold curve extremums (Mirkin A.S., 1966). Therefore, the sensitivity of specialized nervous endpoints to LFAO is determined by their auxiliary structures, especially by the capsule. Ilyinsky O.B. (1966, 1975) has considered the capsule as the resonance oscillation system having maximal amplitude at specific frequencies (also, Chernigovsky V.N. et al, 1970; Mirkin A.S., 1973, 1989).

The frequency ratio comparison of Pacini body responses to acoustic oscillations and vibration (Sato J.M., 1961; Frolov E.P., 1982) has revealed the similarity of frequency-threshold curves. However, the range of maximal vibration sensitivity was found to be wider (100-250 Hz) and the quality factor of frequency-threshold curves was more less. It was concluded that sensorial perception mechanisms are similar to that for vibration.

The nervous endpoint excitation in both cases was supposed (Mirkin A.S., 1966) to be evolved by periodical deformations of the capsule resulted from the energy absorption in its membranes.

The strong increase of Pacini body sensitivity in case of the coincidence of acoustic oscillation frequency and own capsule frequency was named as "biomechanical resonance". It was confirmed by the coincidence of the maximal sensitivity frequency for sound and vibration (100-120 Hz), the rate of potential oscillations in nervous fiber of Pacini bodies (110 s^{-1}), and original frequency of mechanical oscillations of the receptor capsule (100-110 Hz) (Mirkin A.S., 1966).

The main discrepancy of this hypothesis consists in the fact that afferent pulsation does not depend upon acoustic oscillation frequency. By the way, in case of low frequency vibration exposure in Pacini bodies, the correspondence of these frequencies was recorded in several studies (Sato M., 1961; Darian-Smith I., 1984).

The "biomechanical resonance" hypothesis has been unchanged within recent 25 years (Mirkin A.S., 1989). Nevertheless, experiments to confirm this hypothesis were not elaborated as well as studies to prove direct LFAO effects in different cutaneous mechanical receptors.

At recent decade, researchers of Pennsylvania University Medical Center have published the information on established ability of

cutaneous receptors to response to low frequency acoustic oscillations of low intensity. However, they did not provide parameters of applied stimulation and examination methods (Munger B.L., Ide C., 1987, 1988).

For cutaneous mechanical receptors, receptors of locomotor system and internal organs, V.N. Chernigovsky et al have confidently proved the leading importance of mechanical distention of receptor apparatus and surrounding tissues (Chernigovsky V.N., 1960, 1974; Mirkin A.S., 1966; Ilyinsky O.B., 1975). Threshold shift of the mechanical stimulation of Pacini bodies is 0.1-1 μm (Gray J.A.B., Mattews P.B.S., 1951; Frolov E.P., 1982).

G. von Bekesy (1966) has elaborated experiments proposed by G. Meissner (1859) long before, which experiments have demonstrated that human fingers are not sensible to the sound pressure. Only the sound pressure gradient results to the skin surface shift and mechanical dermal receptor response (Bekesy G. von, 1955, 1966).

Some reports (Mirkin A.S., 1989) have discussed the possibility of effective LFAO exposure in biologically active points of the skin. It was demonstrated that own mechanical oscillations of their structures are 8 and 16 Hz. Authors have supposed that acoustic oscillations of such frequencies can initiate "cooperative processes" and provide communication between cells via slit contacts (Mashansky V.F. et al, 1977). At the same time, this supposition was not experimentally proved.

V.O. Samoilov et al (1994) has tried to examine the possibility of LFAO sensorial perception in cutaneous mechanical receptors (see paper below).

Low frequency acoustic oscillation effects in cutaneous mechanical receptors (from Samoilov V.O. et al, 1994)

The LFAO cutaneous perception was examined in single fibers of tibial nerve of rats. The pulsation was recorded using the installation shown by Figure 3.18.

The skin temperature is the most important factor affecting mechanical receptor function (Kleinbok A.J., 1990; Zeeke A.V., 1991; Kleinbok A.J., Gabdulina E.J., 1992). The temperature of foot area of animals was kept at 24-25°C.

Different pulsed mechanical receptor responses were revealed in case of LFAO exposure. Three functional groups of sensorial fibers of tibial nerve were revealed according to recorded responses.

The detailed examination of frequency-threshold curves (5 Hz step) has demonstrated that group I mechanical receptor sensitivity range is unstable. For the majority of receptors, it was 33-250 Hz. The frequency increase from 33 to 100 Hz has induced the significant decrease of threshold power flux density from 12-15 to 1 mW $\cdot$ m^{-2}. In case of the frequency increase to 200-250 Hz, some threshold increases were noted. Followed frequency increase were not found to induce sensorial filament response.

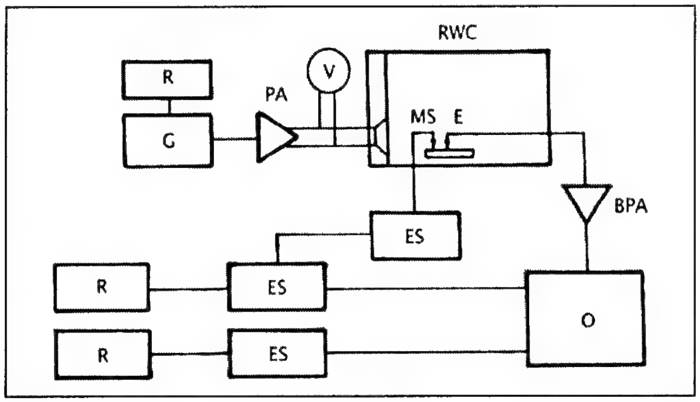
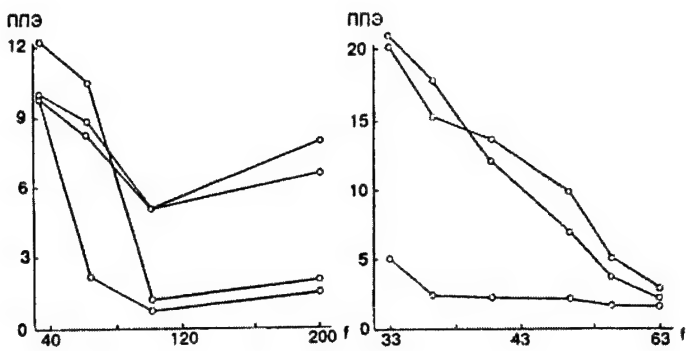


Figure 3.18 - Structural scheme of the installation to examine bioelectric activity of tibial and vagus nerve filaments
G - electric signal generator; PA - power amplifier; V - digital voltmeter; BPA - biopotential amplifier; RWC - running wave chamber; E - leads; MS - mechanical stimulator; ES - electric stimulators; R - rate meter; O - oscilloscope.

Frequency-threshold curves of mechanical receptors of this group are shown by Figure 3.19a. They had two branches of different slopes. Extremums of these curves were at 100 Hz. The approximation of experimental curves in the range of 33-100 Hz has revealed their good correlation to quadratic function.

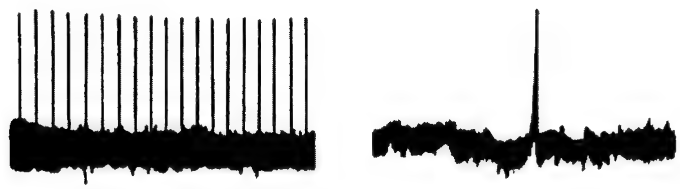


a *b*

Figure 3.19 - Frequency-threshold curves of the first (a) and the second (b) subgroups of cutaneous receptors of group I
Abscissa axis: frequency - f, Hz; ordinate axis: power flux density, PFD, mW·m^{-2}

The other portion of group I sensorial filaments had the upper border of frequency of 65 Hz. Typical frequency-threshold curves are shown by Figure 3.19b. The frequency increase results to the decrease of threshold

power flux densities, though it is less expressed if compared to the previous subgroup. Maximal sensitivity range of these filaments is limited by 55–65 Hz. Threshold power flux densities are 1–10 mW·m^{-2} at specific frequencies.



A B

Figure 3.20 – Spike series recorded in first (A) and second (B) subgroups of mechanical sensorial filaments of tibial nerve (group I) in case of LFAO exposure at 100 Hz (A) and 50 Hz (B)
Power flux density: 10 mW·m^{-2}. Calibration: 20 ms, 100 μV

Pulsed activities of mechanical sensorial filaments were different for these subgroups. First subgroup was specific to single spikes responded to each acoustic oscillation. The spike rate and acoustic frequency ratio was 1:1 (Figure 3.20 A). Pulsed responses of the second subgroup have consisted of one spike (Figure 3.20 B). The power flux density increase (100 times) has not resulted to spike parameter changes and spike number in the pulsed response.

Thus, it was possible to prove that cutaneous mechanical receptors are responsible for sensorial perception of low frequency acoustic oscillations.

In case of the long term LFAO exposure at single frequency, PFD thresholds of group I mechanical receptors were rapidly increased to 250 mW m^{-2} and pulsed activity has disappeared at seconds 20–30. The recovery was observed at minutes 3–5 after the exposure termination. Multiple stimulation of group I mechanical receptors has induced irreversible depression of their pulsed activity.

Frequency-threshold curves of filaments connected to group I cutaneous mechanical receptors (Figure 3.18 and 3.19) were similar to frequency ratios of vibration sensitivity of capsulated nervous bodies of human (Mouncastle V.B. et al., 1972; Skoglund C.R., Knutsson E., 1985; Lamore P.J.J. et al., 1986; Lundstrom R., 1986; Lamore P.J.J., Keemink C.J., 1988; Keroni J. et al., 1989; Morley J., Rowe A., 1990; Horch K., 1991; Tardy M.-F. et al., 1993) and animals (Sato M., 1961; Iggo A., Ogawa H., 1977; Greenstein J. et al., 1987; Zeeke A.V., Yefes E.D., 1992). Curves similar to 3.18 were obtained by A.S. Mirkin (1966, 1973, 1989) in case of LFAO exposure of Pacini bodies.

It can be supposed that LFAO reception is elaborated by capsulated nervous bodies of skin similarly to tactile reception.

This supposition is confirmed by "driving" phenomenon, when the spike rate coincides to acoustic frequency (see Figure 3.20 A). Such reactions were recorded for low frequency vibration (Sato M., 1961; Iggo A., 1977; Greenstein J. et al., 1987; Koltzen M. et al., 1994). The description of these reactions is provided by sensorial system manuals (Fundamentals in sensory..., 1981; Shepperd G., 1987; Eckert R. et al, 1991). The "driving"

phenomenon is established for cutaneous mechanical receptor responses to low frequency acoustic oscillations.

The comparative analysis of frequency-threshold curves of cutaneous sensitivity and Pacini body sensitivity to acoustic stimulation and vibration has revealed their different quality factors. The frequency range of maximal sensitivity is expanded to 100-250 Hz. For LFAO, more expressed frequency selectivity is specific. Lower quality factor of frequency-threshold curves of cutaneous responses if compared to mesenteric Pacini bodies is apparently related to different mechanical properties of dermal structures surrounding cutaneous mechanical receptors.

The significant evidence of cutaneous receptor involvement in LFAO reception includes thresholds of their sensorial perception. The threshold vibration shifts for cutaneous receptors and mesenteric Pacini bodies (at 100-200 Hz) are (1-2) · 10^{-6} m (Mouncastle V.B. et al., 1972; Karpova N.E., Malyshev E.N., 1981; Darian-Smith I., 1984). In the other range of increased vibration sensitivity (30-50 Hz) they are much higher (Lamore P.J.J., Keemink C.J., 1988; Keroni J. et al., 1989).

Our experiments have recorded 10 times difference for acoustic stimulation thresholds in both receptor subgroups. In the first subgroup, minimal amplitudes of the oscillation shifts were (1-2) · 10^{-6} m and (3-7) · 10^{-6} m found in the second subgroup .

The coincidence of threshold amplitudes of oscillation shifts and vibration shifts confirm the supposition about sensorial perception of acoustic oscillations in cutaneous mechanical receptors.

LFAO have suppressed responses of cutaneous receptors of group II. Experiment results are provided by Table 3.17.

Table 3.17 - Relative changes of response thresholds for mechanical stimulation of cutaneous receptors of groups II and III in case of LFAO exposure

Group	Frequency	Response threshold change, %				
		Power flux density, mW· m⁻²				
		1	10	32	50	100
II	33	14±12	23±14*	26+6*		
	63	23±15	37±15			
	100	18±7	28±5			
	200	18±4	33±15		34±17*	
III	33	8±4	15±6	12±7*		
	63	11±5	16±8*			20±10
	100	12±7	20±14*			25±18*
	200	7±6	22±5		17±4	

*Note: M -average value; ±m -confident range of average value (p_a = 0,95); * - confidence level for differences between neighbor values (p>0.05)*

The amplitude of the threshold shift of the mechanical stimulator rod, which amplitude has resulted to pulsed activity in nervous filaments has been increased for 50-200 μm. Table 3.17 indicates that threshold change of pulsed responses was similarly increased at all frequencies with the increase of LFAO power flux density. Such dynamics of the tactile sensitivity was revealed in all mechanical sensorial filaments of group II (Figure 3.21). Statistically confident responses (p<0.05) have manifested from PFD of 1 mW· m^{-2} .

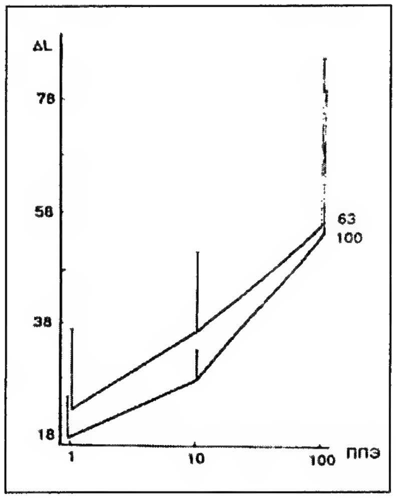


Figure 3.21 - Response threshold changes vs. LFAO power flux density (iso-frequency curves) for cutaneous mechanical receptors of group II
Abscissa axis: power flux density, PFD, mW· m^{-2}; ordinate axis: threshold change - ΔL, % of initial value. Numbers at curves - frequency, Hz

The frequency ratio of the tactile thresholds for similar PFD levels was found to show weak frequency dependence (Figure 3.22). Confident differences ($p>0.05$) of threshold changes were not found at examined frequencies in case of similar PFD values. In case of PFD increase for 1,000 times, the quality changes of observed effects were not found.

The results indicate to small frequency selectivity of mechanical receptor threshold changes in this group. The LFAO influence in tactile sensitivity of mechanical receptors of group II (33-200 Hz) was predominantly determined by power flux density.

The examination of latent periods of mechanical stimulation responses to LFAO is difficult. The depression effect in mechanical receptors of group II is manifested by the increase of threshold amplitudes of the mechanical stimulation (see Figure 3.21). At the same time, the increase of the amplitude itself results to the decrease of latent period of pulsed reactions of mechanical receptors. Therefore, the absolute magnitude of latent period changes (group II receptors) was corrected accordingly. Values are provided by Table 3.18.

Table 3.18 data indicate to the fact that low frequency acoustic oscillations induce confident ($p<0.05$) increase of latent periods of cutaneous mechanical receptor responses since power flux density of 1 mW · m^{-2}. If PFD is increased, latent periods were increased too. Illustrations of obtained dependencies are given by Figure 3.23. Latent period differences were only confident ($p<0.05$), if PFDs were increased for two orders of magnitude.

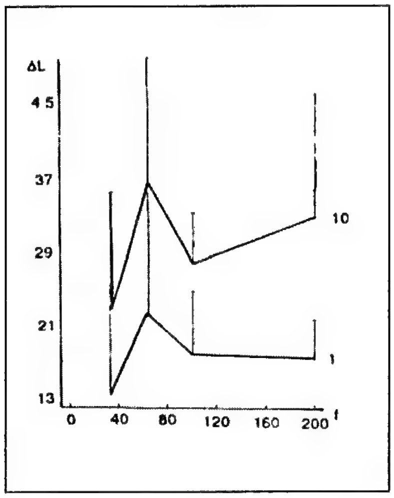


Figure 3.22 - Threshold changes of group II cutaneous mechanical receptors vs. acoustic oscillation frequency (iso-intensive curves)
Legend is similar to that for Figure 3.21

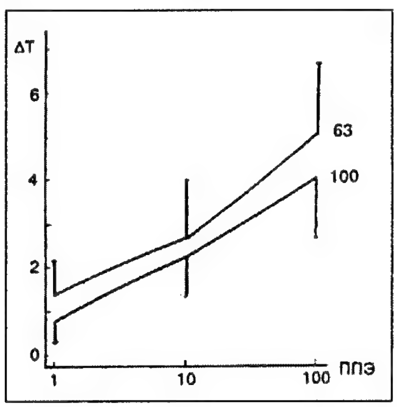


Figure 3.23 - Latent periods of cutaneous mechanical receptor reactions (group II) vs. power flux density (iso-frequency curves)
Abscissa axis: power flux density, PFD, mW· m^{-2} ordinate axis: latent period change - ΔT, ms. Numbers at curves - frequency, Hz.

The frequency ratios of latent period changes for reactions of group II mechanical receptors are shown by Figure 3.24. Confident differences were not found for different frequencies.

Thus, low frequency acoustic oscillations change functional properties of cutaneous mechanical receptors of group II.

The grade of depression of tactile sensitivity is determined by power flux density and does not depend upon LFAO frequency.

Table 3.18 - Latent period changes for groups II and III receptors exposed to LFAO

Group	Frequency	Latent period change, ms				
		Power flux density, mW·m^{-2}				
		1	10	32	50	100
II	33	2.3±1.2	3.1±2.1*	3.8±2.8*		
	63	1.41±0.8	2.7±1.2*			5.1±1.7
	100	0.8±0.5	2.3±0.9			4.1 ±1.4
	200	1.5±0.4	2.1±1.4*		4.2±3.1	
III	33	2.0±1.1	3.2±0.5*	2.0±1.0*		
	63	2.5±1.3	2.8±1.3*			3.5±2.5*
	100	2.8±1.4	3.4±1.8*			4.6±1.4*
	200	1.6±1.4	4.1±3.9*		2.4±1.7*	

*Note: M - average value; ±m - confident range of average value ($p_s \doteq 0,95$); * - confidence level for differences between neighbor values (p>0.05)*

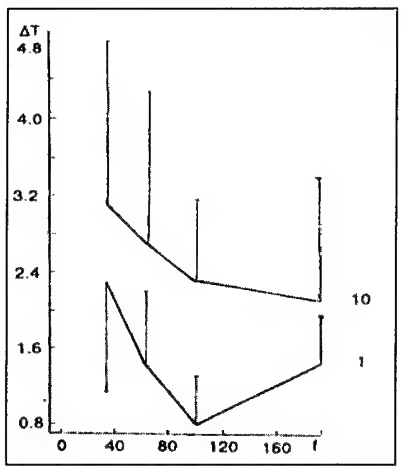


Figure 3.24 - Latent periods of cutaneous mechanical receptor reactions (group II) vs. frequency (iso-intensive curves)
Abscissa axis: frequency - f, Hz ordinate axis: latent period change - ΔT, ms. Numbers at curves - power flux density, PFD, mW·m^{-2}

Group III receptors are specific to changes similar to that for group II, however, they are less expressed. It is certified by threshold and latent period examinations (Table 3.17 and 3.18).

The trend of the threshold elevation was noted for increased power flux density. Dependencies are shown by Figure 3.25.

The tactile sensitivity of mechanical receptors of this group was persisted within the whole period of acoustic stimulation (3 minutes). Threshold amplitude has gradually increased and reached maximum at minute 2 of LFAO exposure. The adaptation rate as well as the grade of tactile threshold change was less in this group if compared to the previous group. The evoked pulsed activity of group III mechanical receptors has persisted in case of changed parameters of acoustic oscillations.

Similarly to group II mechanical receptors, the grade of the depression of mechanical receptor sensitivity did not depend upon the frequency (Figure 3.26). At all frequencies, the threshold differences were of low significance level (p>0.1) in case of the same power flux density.

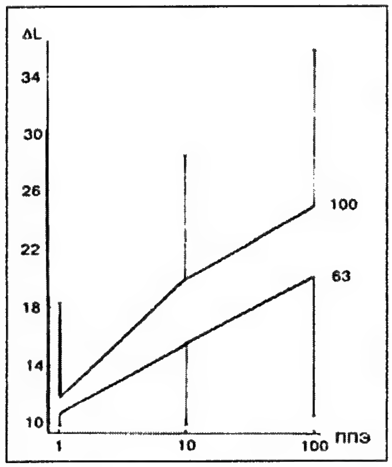


Figure 3.25 - Response threshold change (cutaneous mechanical receptors of group III) vs. power flux density (iso-frequency curves)
Abscissa axis: power flux density, PFD, mW· m⁻²; ordinate axis: threshold change - ΔL, % of initial value. Numbers at curves - frequency, Hz

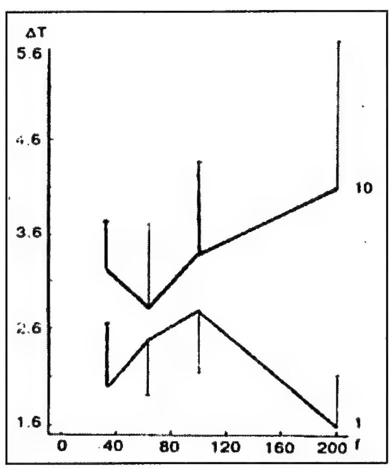


Figure 3.26 - Response threshold change (cutaneous mechanical receptors of group III) vs. frequency (iso-intensive curves)
Abscissa axis: frequency - f, Hz: ordinate axis: threshold change - ΔL, % of initial value. Numbers at curves - power flux density, PFD, mW· m⁻²

The increase of latent periods of responses of group 3 receptors has also occurred (see Table 3.17). At 33 and 200 Hz, maximal change of latency was found for 10 $mW \cdot m^{-2}$ PFD (Figure 3.27). The frequency selectivity was not found (Figure 3.28).

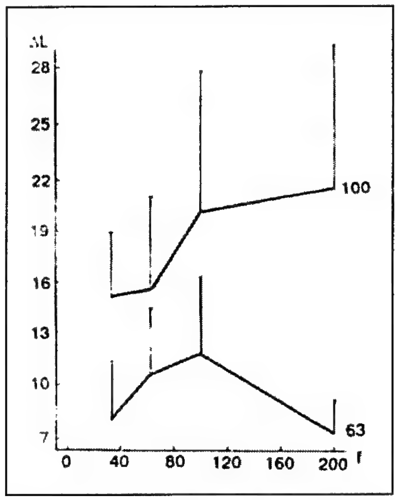


Figure 3.27 - Latent period amplitudes (group III receptors) vs. power flux density (iso-frequency curves)

Abscissa axis: power flux density, PFD, $mW \cdot m^{-2}$; ordinate axis: latent period change - $\Delta\_$, ms. Numbers at curves - frequency, Hz.

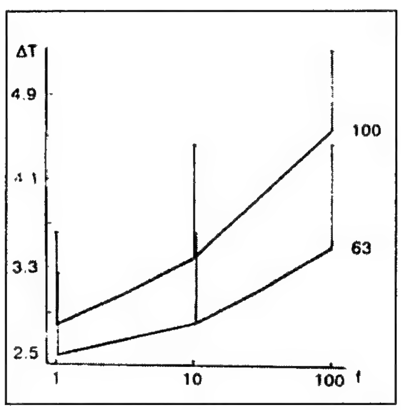


Figure 3.28 - Latent period amplitudes (group III receptors) vs. frequency (iso-intensive curves)

Abscissa axis: frequency - f, Hz; ordinate axis: latent period change - $\Delta\_$, ms. Numbers at curves - power flux density, PFD, $mW \cdot m^{-2}$

Therefore, the dynamics of function properties of group III receptors (similarly to group II) was basically determined by power flux density rather than acoustic oscillation frequency. The latent period increase for groups II and III receptors could be correlated to the effects in filament and sensorial terminals as well. The acoustic stimulation has not changed amplitude and duration of spikes transmitted via single nervous filaments. Besides, after the exposure termination, the gradual increase of the excitation conduction velocity was noted for nervous filaments of groups II and III, which was expressed by the latency recovery.

LFAO exposure has changed the cutaneous metabolism. The interstitial oxygen pressure dynamics was evaluated as the integral index of the cutaneous metabolism (Gejrovsky J., Kuta J., 1967; Berezovsky V.A., 1975; Franzeck U.K. et al., 1982; Prokhorov G.G., 1989). LFAO have induced pO_2 decrease in the skin.

The oxygen pressure decrease in intra-cellular cutaneous area could be resulted both from the increased consumption (including consumption in mechanical receptors) and by the delay of blood flow in the capillary network. However, it is known that the intensity of oxidative-recovery reactions in free nervous endpoints and capsulated nervous bodies of the skin is not high (Darian-Smith I., 1984; Akoev G.N., Alexeev N.P., 1985).

Epidermal stem cells and dermal microstructures are not specific to high metabolism activity, so the oxygen consumption is low. Therefore, metabolism change in mechanical receptors and other cutaneous elements are hardly possible and insufficient to significantly affect oxygen pressure dynamics around mechanical receptors.

Blood vessels are absent in epidermis and nutrition is arranged via inter-cellular lymph slits (Frolov E.P., 1982). The cutaneous mechanical receptor vascularization pre-causes the direct correlation between oxygen pressure in dermal microstructures and cutaneous blood flow. The correlation coefficient is 0.61-0.99 for different skin sites (Prokhorov G.G., 1989).

In case of the long term LFAO exposure, the cutaneous temperature decrease was found in extremities, which indicates to the peripheral blood flow decrease (Karpova N.I., Malyshev E.N., 1981). Therefore, the observed blood flow decrease are possibly related to the blood flow change in dermal microcirculatory basin rather than to increased oxygen consumption on cutaneous mechanical receptors.

It should be noted that oxygen pressure changes were 10-25 mm and were statistically significant at LFAO power flux densities above 100 mW $\cdot$ m^{-2}. Mechanical receptors of group I are able to perceive low frequency acoustic oscillations of 100 times lowed PFDs. At the same PFDs, the tactile sensitivity of mechanical receptors of groups II and III is confidently changed too. Thus, cutaneous, mechanical receptors react to LFAO stimulation, when the cutaneous metabolism is unchanged.

It is known that oxygen pressure is decreased in case of the exposure to different interior and exterior factors (Berezovsky V.A., 1975; Kislyakov Yu.A., 1987). The expressed changes of this index were found for low frequency acoustic oscillations. However, the comparison of the thresholds and latent periods of occurred polarographic and pulsed responses suggests that shifts of tissue oxygen consumption occur at more significant PFDs than mechanical receptor responses. Therefore, the low intensive LFAO "target" involve cutaneous receptors.

The obtained results demonstrate that LFAO induced depression in tactile sensitivity of mechanical receptors is mildly related to the metabolism rate in the skin. Local microcirculation changes can affect mechanical

sensorial function in case of significant power flux density of long term LFAO exposure.

Thus, V.O. Samoilov et al (1994) have got experimental evidences of the fact that *low frequency acoustic oscillations induce low threshold mechanical receptors of the skin*, which receptors were identified to be Pacini-like and glomulus capsulated bodies able to signalize to that kind of the unfavorable environmental factor. The frequency dependence of pulsed reactions of Pacini-like capsulated nervous endpoints is of non-monotone character with maximum at 100 Hz.

LFAO do not induce pulsed responses in filaments transmitting signals from middle and high threshold mechanical cutaneous receptors identified like free nervous endpoints; alternatively, LFAO depress their sensitivity. The sensitivity thresholds of these groups of mechanical receptors are increased as well as the latency periods of their reactions to adequate mechanical stimulation at any frequency of acoustic stimulation. The grade of function changes in mechanical sensorial terminals of high tactile thresholds is determined by power flux density and is not depend upon LFAO frequency. The depression of the tactile sensitivity induced by LFAO and followed depletion of pulsation transmitted from cutaneous receptors to CNS can result to sensorial deprivation and cause multiple psycho-emotional disturbances.

3.2. LFAO effects in cardiovascular system

The expressed cardiovascular system reaction was noted for LFAO exposure.

At 10 Hz and 135 dB, N.I. Karpova et al (1981) have examined AP and pulse rate. Clear pulse rate elevation was found (average increase of 11 ± 3 min^{-1}) in the majority of examinees. Maximal and minimal AP values have been changed after 15 min exposure: though maximal AP was increased insignificantly. The minimal AP was significantly increased (for 9 ± 2 mm, in average). Changes were unstable and have been recovered 25-35 min thereafter.

P. Borredon, J. Nathie (1973) (7.5 Hz and 130 dB; 50 min exposure) have noted the pulse rate decrease for 3 min^{-1}; maximal AP was decreased for 2.9 mm and minimal AP was increased for 1.8 mm. Changes were unstable and have recovered at minutes 15-20 after the exposure termination.

R.W. Stephens (1974) has noted that LFAO have not significantly changed blood counts and endocrine reactions but some increase of pulse rate and breath rhythm were found.

N.I. Karpova et al (1981) have found ECG signs of cardiac rhythm disturbance. Q—T interval extension was noted at 5 Hz and 135 dB in 55% examinees, and in 33% examinees at 10 Hz; changes were most frequent at 15th minute of the exposure.

At 5 and 10 Hz and 135 dB, peculiar pulse rate changes were observed. At first minutes, the elevation was found for both frequencies. At minutes 5-10, the pulse rate was delayed and it was lower than the baseline value after the exposure termination. These data coincide to P. Borredon, J. Nathie (1974), who has revealed similar changes for 130 dB infrasound.

REG data obtained by N.I. Karpova et al (1981) are provided by Table 3.19.

Table 3.19 - Hemodynamics changes in case of the infrasound exposure (REG data)

Examination conditions	REG indices			
	Rheography index	Anacrotic phase (%)	Catacrotic phase (%)	Tonic pressure indices
5 Hz, 135 dB				
Before exposure	1.20	12.9	0.79	1.70
During exposure within:				
1 min	1.25	13.4	0.79	1.60
7 min	1.31	13.4	0.77	1.53
15 min	1.37	14.4	0.77	1.53
After exposure	1.32	13.8	0.78	1.59
10 Hz, 135 dB				
Before exposure	1.22	11.7	0.75	2.53
During exposure within:				
1 min	1.35	12.5	0.75	2.35
7 min	1.37	12.9	0.75	2.38
15 min	1.37	12.6	0.76	2.18
After exposure	1.32	12.7	0.75	2.18

Thus, experiments indicate to cerebral circulation changes including rheography wave amplitude increase, anacrotic phase expansion and tonic tension decrease in intracranial vessels. The infrasound induced depression of cerebral hemodynamics has been found including the venous outflow complication and intracranial hypertension. At 10 Hz and 135 dB, more persisted cerebral hemodynamics changes were noted if compared to 5 Hz.

These data agree with V.I. Vasiliev (1976), who has examined microcirculation of mild meninx in white rats exposed to the infrasound.

The constrictive cardiac function examination demonstrates that the amplitude was decreased; most expressed shifts were noted at 10 Hz. Besides, at 5 and 10 Hz and 135 dB, the mechanical shifts of the heart were noted together with decreased cardiac constriction force.

N.I. Karpova et al, (1981) have examined infrasound effects in peripheral blood circulation of human.

The chamber with infrasound frequency of 10 Hz and 135 dB was used. 15 min exposure was applied. Males of 20 to 25 years ages were examined. Peripheral blood circulation was investigated before and after the exposure (plethysmography techniques).

Data have demonstrated that peripheral circulation is changed under the infrasound exposure (Figure 3.29). Immediately after the infrasound exposure termination, clear confident decrease of the pulse rate (6-8 min-1, in average) was noted. However, it was found that blood flow has increased for almost 20-22% versus baseline.

At the same time, the functional test of the breath stop has indicated to expressed trend of vascular expansion. Found changes were unstable and came to the baseline at minutes 10-15 min.

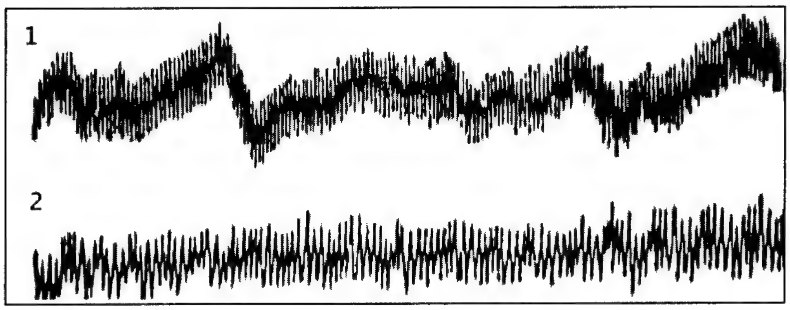


Figure 3.29 - Plethyzmogram at norm (1) and after 15 min exposure at 10 Hz, 135 dB (2) (Karpova N.I., Malyshev E.N., 1981)

Thus, the peripheral circulation is sensible to 15 min exposure at 10 Hz and 135 dB.

AP examinations have also demonstrated the infrasound intensity dependence. For 100 dB and 5 Hz, insignificant AP changes were noted. The systolic pressure (68% of examinees) and diastolic pressure (79% of examinees) were unchanged and found changes were below 5 mm.

In case of 90-120 dB, the pulse rate mismatch was noted with increased dispersion of R-R-intervals (Petounis A. et al., 1977; Mozhukhina N.A., 1979). The increasing intensity has induced increased changes of cardiac bioelectric activity.

Confident changes of the pulse rate of different directions and magnitudes were found in experiments (Alford B.R. et al., 1966; Jonhson D.L., 1972; Stephens R.W., 1974; Parker D.E., 1976).

V.O. Samoilov et al (1994) has examined cardiac rhythm in rats according to cardiac automatism change (R-R- duration). LFAO have induced confident R-R-interval changes at seconds 1-5 of the exposure (Figure 3.30).

In 74% of cases the decrease of cardiac cycles was noted. The data conclude to the fact that low frequency acoustic oscillations induce confident ($p<0.01$) increase of the pulse rate. The range of absolute change of R-R-intervals was 4-10 ms. R-R-intervals were 200-350 ms. Some tests (<13%) had R-R-interval change of > 10

ms. At seconds 20-30 of the exposure the cardiac automatism level came back to the baseline in 86% of cases.

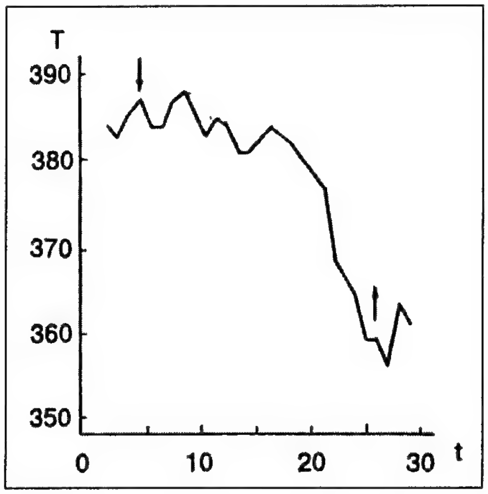


Figure 3.30 – R-R-interval dynamics in case of LFAO exposure at 33 Hz and power flux density of 10 $mW \cdot m^{-2}$
Abscissa axis: time – t, c; ordinate axis: cardiocycle duration – T, ms.
Arrows indicate to the beginning and termination of the exposure

Significant positive chronotropic effect was observed. The probability of effect was directly proportional to power flux density (Table 3.20).

Table 3.20 demonstrates that the power flux density increase results to the increase of the probability of R-R-interval changes. For power flux density of 1 $mW \cdot m^{-2}$, it is more than 50%.

Table 3.20 – Probability of R-R-interval change in rats exposed to LFAO

Frequency, Hz	Probability of R-R-interval change, %, for power flux density, $mW \cdot m^{-2}$			
	0.1	1	10	100
33	7	63	58	87
63	14	54	57	93
100	10	50	73	82
200	13	–	65	–

LFAO have induced the same probability of R-R-interval decrease at all frequencies (Table 3.20). Therefore, the frequency selectivity of induced cardiac activity changes is absent.

Systolic pressure changes were insignificant (Karpova N.I., 1979; Karpova N.I., Malyshev E.N., 1981). The diastolic pressure increase was correlated to venous outflow decrease (Borgmann R., 1988;

Paranko N.M., Madatova R.B., 1990) and to the increase of vein tone (Borredon P., Quandieu P., 1977), as same as to the vascular regulation disturbance resulted from changed cerebral hemodynamics (Reutov O.V., 1976). Cerebral hemodynamics changes were expressed and stable: REG-wave amplitude increase, anacrotic phase increase and skeleton muscle tone decrease (Karpova N.I. et al, 1972, 1979; Mozhukhina N.A., 1979).

Together with change of cardiovascular system function, low frequency acoustic oscillations of 90 to 140 dB have induced expressed morphological changes of myocardium and vessels of different types.

The cardiac muscle was found to contain dystrophic foci with decreased glycogen content after the single LFAO exposure. Points of over-constriction of muscular fibers were noted. The edema of connective tissue filled with infiltrate leukocytes was found (Alexeev S.V. et al, 1983; Nekhoroshev A.S., Glinchikov V.V., 1990).

At 2-63 Hz octaval frequencies and 90-140 dB, the myocytolysis and cardiomycyte enlargement have resulted to stasis in capillaries, veins and venulas of the heart, coronary endothelium edema, perivascular hemorrhages, capillary expansion (Shutenko O.I. et al, 1979; Alexeev S.V. et al, 1983; Glinchikov V.V., Nekhoroshev A.S., 1990; Nekhoroshev A.S., Glinchikov V.V., 1990, 1991). In ischemic foci of the myocardium, the strong contraction of capillaries was noted due to endothelium cell enlargement. LFAO have induced lymphatic capillaries expansion with interstitial leakage of lymphocytes (Glinchikov V.V., Nekhoroshev A.S., 1990).

The myocardial activity of cytochrome oxidase, glycolysis ferments (glucose-6-phosphate dehydrogenase, α-glycerophosphate dehydrogenase) and tricarbonic acid cycle (malate dehydrogenase) were examined (Sanova A.G., 1975; Shutenko O.I. et al, 1979; Svidovy V.I., Shleykin A.G., 1987; Nekhoroshev A.S., Glinchikov V.V., 1990, 1991). The succinate dehydrogenase activity in cardiomyocytes has varied depending upon the exposure duration (Glinchikov V.V., Nekhoroshev A.S., 1990).

LFAO have also induced significant change of peroxide lipid oxidation in myocardium (Mkhitaryan V.G. et al, 1988). The long term exposure has induced pro-oxidative systems activation (Dadali V.A. et al, 1992). Followed compensatory increase of antioxidative system activity with increased glutation and superoxide dismutase concentrations was most expressed at day 7 after the exposure beginning (Svidovy V.I. et al, 1987; Dadali V.A. et al, 1992). The conclusion was drawn to the increased cellular damage in case of the long term acoustic exposure i.e. to the cumulative effect.

Expressed changes have occurred in the vascular basin of organs and tissues. LFAO have induced the disorder of hemato-lymphatic basin of the conjunctive (Svidovy V.I., Kuklina O.I., 1985) and decrease of unstriated muscle constriction of portal vein in rats

(Alexeev S.V. et al, 1983). Significant changes have also occurred in mild meninx microcirculation in rats (Vasiliev V.I., 1976).

These morphological shifts were similarly observed at different infrasound frequencies. The expressiveness of these changes has increased for increased SPLs and exposure times.

S.V. Alexeev et al (1983) has examined infrasound effects in myocardium applying microscopy techniques.

The infrasound source has provided 0.5 to 50 Hz and 90 to 150 dB in the experimental chamber (Karpova N.I. et al 1972; Malyshev E.N. and Pronin A.P., 1972).

The intensity maximum was at the specified frequency and octaval difference was 28 to 41 dB.

Guinea pigs and white rats were exposed at 4 to 16 Hz and 90 to 145 dB within 45 days (3 h/day). Each group was composed of 5 animals including 2 controls.

Single infrasound exposure at 4-6 Hz and <100 dB has not been found to induce expressed myocardial changes. Single infrasound exposure at 4-10 Hz and 120-125 dB has induced short-time decrease of arterial diameter and capillary expansion. The resulting ischemia of focal character with followed damage of myofibrillation apparatus was found. Most frequently, the single infrasound exposure results to the intra-cellular myocytolysis. Such processes are reversible and do not result to myocardial pathology.

The longer infrasound exposure of above mentioned frequencies and intensities (5, 10, 15, 25 days) results to ventricle fibrillation and sub-segmental contractures in ischemic foci. Electronic microscopy indicates to myofibril fragmentation in Z-stripes; sarcoplasmatic reticulum structures are disappeared, cellular nuclei are deformed and chromatin is accumulated under the nuclear membrane.

Intracellular regeneration occurs together with damage. In survived cells, the amount and size of mitochondrias is increased and myofilaments are created as well as sarcoplasmatic reticulum elements. The intracellular regeneration is slow and finished with Z-stripes creation. Myofibrils become normal and myocardiocytes are completely recovered.

The experimental results certify to the fact that myocardial changes induced by the infrasound exposure at 4-10 Hz and 120-125 dB are reversible.

More expressed myocardial damages were found in case of the single exposure at 10-15 Hz and 135-145 dB. Hemorrhages of emigration character have been found in the heart sites, which damages result to myocardiocyte dystrophy. Damaged cells are constricted and contractured including nuclei pyknosis and chromatin redistribution to the nuclei membrane.

In case of singe infrasound exposure at 10-15 Hz and 135-145 dB the partial death of myocardiocytes was noted; less damaged cells have demonstrated the intra-cellular regeneration within 5-10 days.

The long term daily infrasound exposure at 4-8 Hz and 120-125 dB is specific to myocardial ischemia with more disseminated damage of focal character, which is basically localized in myofibril, which affect the cardiac function. In case of the exposure termination, intracellular regeneration is more prolonged if compared to that in case of single infrasound exposure.

Much more expressed myocardial changes were found in case of the long term exposure at 10-15 Hz and 135-145 dB. The persisted myocardial

ischemia related to the vascular damage is accompanied by cardiocyte damage. Less damaged cells demonstrate the intracellular regeneration followed to myofibril fragmentation and partial damage of sarcoplasmatic reticulum.

At days 15-25, the recovered cells initiate normal function, however, abnormal structures are present in the cytoplasm; it is essentially related to new mitochondrias, which are sometimes giant.

The study has demonstrated that the infrasound exposure at different frequencies and intensities has induced myocardial ischemia resulted from main vessel spasm and mosaic damage of myocardiocytes. Control animals were not found to develop morphological changes in myocardium.

The ischemic processes are increased within the exposure time and can result the cellular destruction. The essentially expressed myocardial effect was noted for the infrasound exposure at 10-15 Hz and 135-145 dB. Even single (3 h) exposure induces the death of some myocardiocytes positioned in the central target area. Destruction processes are increased within the exposure time and myocardiocyte damage area is enlarged; necrotic cells are destroyed by polyblasts and microscarring is occurred.

The myocardial recovery is based upon the intracellular regeneration of mildly damaged myocardiocytes; it takes long time, which obviously affect myocardial function.

M.Yu. Safonov (1978) has examined histoenzymatic features of the myocardium and concluded that the infrasound exposure induces early and progressing changes of the ferment activities. These ferments are related to myocardiocyte mitochondrias and pathological changes are most expressed in the cardiac compartments of high constrictive function.

Method. 40 male rabbits (2.6-3 kg body weight) were exposed to the infrasound to reveal the activity and topochemistry of succinate dehydrogenase (SDH) and cytochrome oxidase (CCO) in myocardiocytes. The exposure was at 10 Hz and 100-110 dB (24 days; 6 h/day) (Fryman B.J. et al). SDH activity was assessed after incubation with chlorine neotetrasol (according to Aronson), and CCO activity was examined according to Bilsky. The light microscopy was applied to topical slice scans.

Since day 3 of the exposure, progressing dystrophic changes of myocardiocytes were found as well as eozinophilia and sarcoplasm eozinophilia, fuchsinophil degeneration of myocardial cells in sub-endocardium and upper cardiac compartments.

At day 3 of the exposure, sarcoplasmatic myocardiocyte area was found to accumulate agglutinating Formosan granules. Microdensitometry examinations have established SDH excess (124% ($p=0.05$)) in the left ventricle and mild decrease (98%) in the right ventricle septum and inter-ventricle septum, if compared to control animals. The right ventricle septum was specific to insignificant SDH activity increase in the sub-endocardium area.

CCO activity was elevated at day 3 in septa of left and right ventricles for 126% ($p<0.05$) and 120%, respectively; inter-ventricular septum activity was decreased to 93%. In the left ventricle septum, the relative CCO increase was noted in sub-endocardium area (128% ($p<0.05$). The inter-ventricular septum CCO activity was decreased in sub-endocardium area (67%) ($p=0.05$).

Followed exposure (day 6) has resulted to significant increase of cellular territories of expressed change of Formosan distribution including sub-endocardium and middle areas of the left ventricle myocardium and inter-ventricular septum.

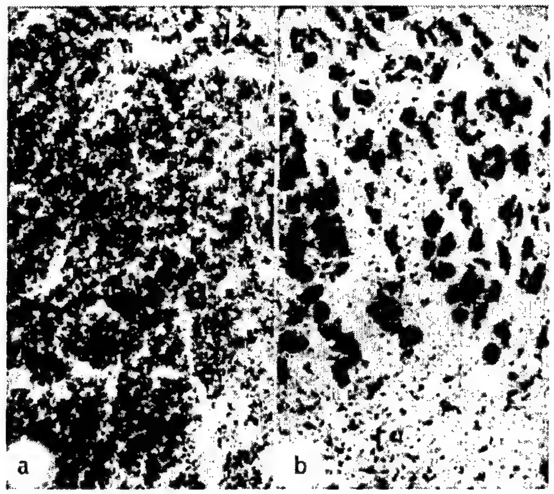


Figure 3.31 - Succinate dehydrogenase activity in left ventricle myocardium at norm (a) and after infrasound exposure within 18 days (b)
Cryostat. Incubation in chlorine neotetrazole according to Aronson (pH 7.6). 10 x 7

Thus, above-mentioned results of experimental studies and volunteer observations have demonstrated the principal possibility of cardiovascular LFAO effects. However, the importance of these effects should not be overestimated. The volunteer studies tried in the Institute of Biophysics 1976-1985) have provided cardiovascular effect data for a number of indices (AP, pulse rate, ECG etc), however, these changes were unstable and transient.

Major morphological findings confirmed are changes related to hemodynamic and microcirculatory disturbances.

3.3 LFAO effects in pulmonary system

A number of references indicates to infrasound effects in respiratory system. P. Grognot (1959) has noted breath complications and increased breath rate as well as cough in examinees. D.L. Johnson (1972) has found that infrasound of < 10 Hz and ~170 dB has not significantly affected the animal breath but breath stop was noted. It was supposed that air flow related to the pressure change was sufficient to get lung ventilation.

A number of studies indicate that LFAO induce the change of the breath rhythm and chest vibration. Examinees have reported to these phenomena and they were observed by researchers in many cases. These observations were done at 4 and 25 Hz; at 8 Hz they have manifested for 132 dB only. At 2 Hz and below, the chest oscillations were not observed.

N.I. Karpova et al (1981) has examined infrasound effects in respiratory function. Pneumography was applied before exposure, at minutes 1, 7 and 15 and at recovery period; pulse rate was measured simultaneously.

The exposure to 135 dB has induced breath rate decrease most expressed at 5 Hz. The examinees majority has been found 12.7% average breath rate decrease at the first minute. At minute 7 the breath rate was 15.8 per min (2.4 breaths less versus baseline); at minute 15 the breath rate was 16.1 per min. After the exposure termination, some breath rate increase was found.

At 10 Hz, the complicated breath and chest vibration were noted in lower percentage of examinees.

V.O. Samoilov et al, (1994) have examined breath response according breath rhythm dynamics. The pneumogram was analyzed to assess breath pattern form and breath cycle phase periods.

LFAO of power flux density above 1 mW $\cdot$ m^{-2} have induced significant breath changes. General time of the respiratory system reaction was less for 15 s. alternatively to pulse rate changes, breath reaction were of opposite direction i.e. the breath rate decrease was found.

Bradypnea was noted in 87% of tests. Such respiratory reaction dynamics was confidently ($p<0.01$) different versus the baseline. The breath cycle duration in the majority of tests (> 80%) has varied within 70-250 ms with total duration of 800-3,500 ms. In some tests the response was 500-600 ms. The typical variant of pneumogram change is shown by Figure 3.32.

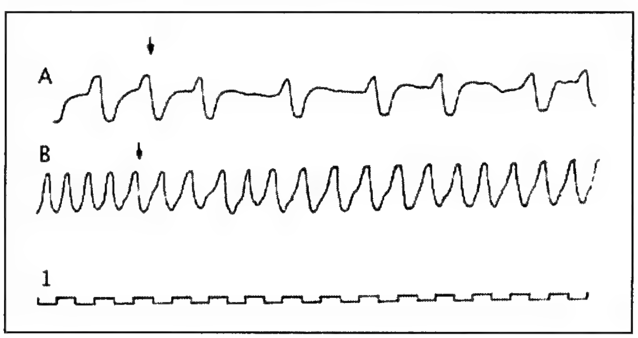


Figure 3.32 - Pneumogram change variants in rats exposed at 33 Hz (A) and 63 Hz (B); power flux density of 10 mW$\cdot m^{-2}$
1 - time mark (1.5 s cycle); ↓ - acoustic exposure beginning

The probability of the respiratory effect has depended upon power flux density at all examined frequencies (Table 3.21).

Table 3.21 - Probability of respiratory cycle duration change in rats exposed to LFAO

Frequency, Hz	Probability of respiratory cycle duration change, % for power flux density, mW · m^{-2}.			
	0.1	1	10	100
33	25	54	44	86
63	36	38	58	80
100	50	57	79	77
200	50		58	

Table 3.21 demonstrates that the increase of power flux density results to the increase of probability of the breath cycle duration increase. Such increase was noted for power flux density of 1-10 mW · m^{-2}.

For different frequencies, the probabilities have not been significantly different (Table 3.21). Amplitudes of the respiratory response were also similar. These observations indicate to low frequency selectivity of the respiratory response in case of LFAO stimulation.

The inspiration phase increase was found in 94% of effective exposure cases, which indicates to statistically significant effect ($p<0.01$). Absolute values of inspiration phase increase were 50-200 ms and they did not depend upon the acoustic frequency. The correlation of the breath cycle increase versus inspiration phase increase was found ($r = 0.91$; $p<0.05$).

The form of the respiratory pattern was affected by low frequency acoustic oscillations. Pneumograms had several peaks at the inspiration phase, which irregularity has certified to the disturbance of the breath rhythm (Figure 3.33). Such effects were noted at all frequencies.

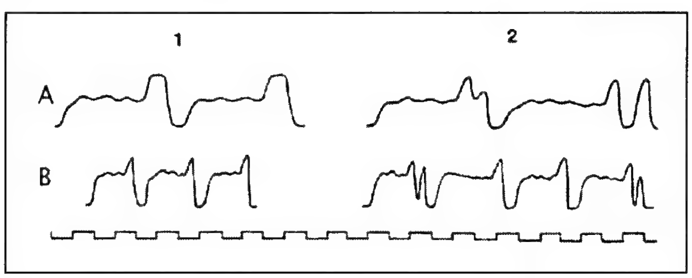


Figure 3.33 - Variants of respiratory pattern changes at 100 Hz (A) and 63 Hz (B); power flux density of 10 mW · m^{-2}

1 - before exposure; 2 - after exposure. Cycle time mark - 1.5 s

It was shown that low frequency acoustic oscillations at 2–16 Hz and 90–140 dB have induced large hemorrhage foci in connective tissue septa of bronchi-pulmonary elements, blood stasis in capillary and venous alveolar networks. Mosaic hemorrhages were found in alveolar capillary membranes of rats (Svidovy V.I., Glinchikov V.V., 1987).

Experiments were tried in male rats exposed at 2, 4, 8 and 16 Hz and 90–140 dB (40 days; 3 h/day). 10 animals were in each group including 3 controls. The autopsy was done at hour 3 after the acute exposure and at days 5, 10, 15, 24 and 40.

The electronic microscopy (JEM-7A) was tried in slices (LKB-III) with lead citrate contrast.

Acute 3 hour irradiation at 2 and 4 Hz and 90–100 dB has induced single mosaic hemorrhages under the pleura in the whole lung surface. More expressed microscopic changes of fresh sub-pleural hemorrhages were found in animals exposed at 8 Hz and 110 dB. Large hemorrhage foci were revealed at 8 and 16 Hz and 120–140 dB.

The increase of fine vessel diameters was found at 2 and 4 Hz and 90–110 dB, which have resulted to large hemorrhages and peri-vascular edema. Such vascular changes were localized in alveolar capillary network and post-capillary venulas. Strong erythrocyte overflow in alveolar capillaries was found at 8 and 16 Hz and 110 dB, which, apparently, results to gaseous metabolism disturbance in damaged acinuses. It follows to expressed morphological changes in arterial plexus under the mucosa, in large and fine bronchi.

At 8 and 16 Hz and 120 and 140 dB, the lung tissue was found to contain vast hemorrhage foci localized in connective tissue septa of bronchi-pulmonary segments, where ruptures of fine vessel walls were noted in some cases. In respiratory compartments, the released erythrocytes were accumulated in acinus system, which results to strong deformation of alveolar pathways. In some preparations, the alveolar sacculus ruptures were observed with consequent deformation.

In all experiments, it was found that capillary changes are followed by alveolar epithelium desquamation and basal membrane denudation; the attached capillaries are overfilled by erythrocytes, which are released to inter-alveolar septa.

At 8 Hz and 120 dB, the plane cells, type I pneumocytes, are changed. The length and number of microvilli are decreased in the alveolar cavities. The deformation of cellular nuclei is occurred with chromatin re-distribution to the nuclear membrane. Simultaneously, the changed cells have deformed or enlarged mitochondrias with crest shortage.

Secretion cells, type II pneumocytes were observed to have nuclei deformation with chromatin re-distribution to the nuclear membrane. Besides, these cells were noted to have mitochondria

changes, which disturbs cellular metabolism. The lipoprotein production is disturbed, which delays the damaged alveoli regeneration.

These data indicate that initial damage of structure and function of cells is significant for infrasound effects. The described processes are specific to recovery after the infrasound exposure termination.

In case of the long term exposure at 8 Hz and 120 dB, a portion of acinuses is filled with erythrocytes, which appear in the air guide pathways. At day 5, the blood released from damaged vessels has created hemorrhage foci in interstitial tissue, which results to strong deformation of respiratory bronchioles. At days 10 and 15, lung tissue sites completely filled with spilled blood were observed; inter-alveolar septa are thicken due to the edema. Large number of leukocytes is accumulated in the mosaic damage areas of the lung tissue; polyblasts and macrophages appear later to participate in died cell lysis.

In case of infrasound exposure termination, respiratory bronchioles and alveolar pathways of damaged acinuses are cleared from exudate; the deformation and edema of inter-alveolar septa disappear and damaged lung sites are completely recovered.

In case of the long term exposure at 8 and 16 Hz and 140 dB, the vascular wall ruptures and acinus damage have occurred, which results to the decrease of alveolar lumen and to the poorly differentiated cells growth in the alveolar surface, which cells are unable to produce surface alveolar complex (Figure 3.34). However, in relatively undamaged alveolar structure, the activation of type II pneumocytes is observed. These cells have well developed endoplasmic reticulum and large number of mitochondrias as well as the multivesicular bodies and plate structures (Figure 3.35).

Major components of plate structures are produced by the endoplasmic reticulum and Holdgi complex. Hypertrophy of such secretion cells results to increase of pulmonary surfactant production to promote normal alveolar function.

The pathomorphological examinations have demonstrated that even single infrasound exposure at 2 and 4 Hz and 90–110 dB has induced vascular endothelium damage resulting to hemorrhages to pulmonary tissue and lumen of respiratory bronchioles and acinuses. The pneumocyte damage is also observed in alveoli. However, these events are reversible and damaged lung tissue is recovered after the exposure termination. Lung tissue changes depend upon the frequency and exposure duration; the intensity ratio is less expressed, which is apparently related to resonance oscillations in alveolar tissue. In case of infrasound exposure at 8 Hz and 120 dB within 25 and 40 days, the death of some pneumocytes is observed with denudation of underlying tissue and followed destruction of alveolar walls. Such processes are of local

character with mosaic damages resulted from vascular wall ruptures and hemorrhages.

Figure 3.34 - Electronic view of plane pneumocytes of type I (1). Alveolar lumen is strongly decreased (2)
40 day exposure. x 11,000

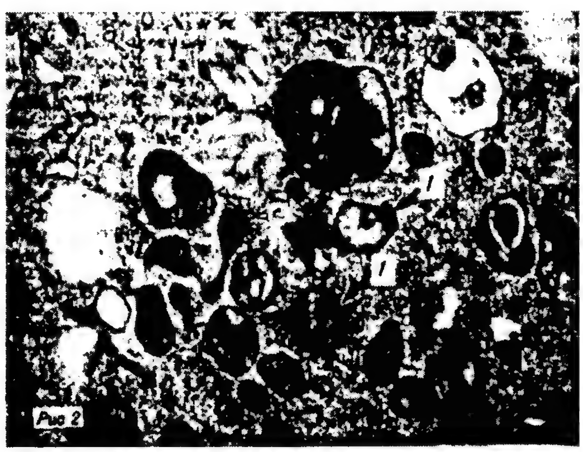


Figure 3.35 - Ultrastructure of type II pneumocyte. Cytoplasm of secretion cell contains large amount of plate bodies (1), participated in the production of pulmonary surfactant

The exposure at 8 and 16 Hz and 140 dB is essentially harmful for lungs, because the resonance results to the rupture of larger vessel walls despite of alveoli walls.

Thus, the expressiveness of lung changes is proportional to acoustic intensity. For SPLs of > 130 dB, alveolar wall ruptures and expressed endothelium cell damages were found, which has resulted to hemorrhages in pulmonary acinuses and larger bronchi lumen (Svidovy V.I., Glinchikov V.V., 1987). In case of LFAO exposure of significant sound pressure level, the significant air volume is present in lungs, which volume cannot be evacuated via air guide pathways and deforms lung tissue. Due to the law fastness of lung parenchyma, the ruptures of alveoli and acinus hemorrhages are possible, essentially for 185 dB (Grognot P. et al., 1959) and shock trauma (Dyachenko A.I., Lubimov G.A., 1988). At the same time, the character and expressiveness of vascular basin changes in both myocardium and lungs certify to their similarity.

3.4 LFAO effects in digestive system

LFAO effects in digestive system are poorly described in literature and basically related to hepatic structures examination including hepatocytes.

The long term LFAO exposure of >110 dB has induced hepatocyte nuclei deformation with chromatin re-distribution and RNA content increase in cytosol (Svidovy V.I., Borshukov D.V., 1988; Nekhoroshev A.S., Glinchikov V.V., 1990, 1992). Small drop fatty hepatic dystrophy was observed, which expressiveness was proportional to sound pressure level (Shutenko O.I. et al, 1979).

Despite expressed morphological changes, the hepatic metabolic activity dynamics was observed in rats. Tricarbonic acid cycle has been changed as well as the ferment activity of oxidative phosphatation, glycolysis and lipolysis (Sanova A.G., 1975; Shutenko O.I. et al, 1979; Svidovy V.I., Sleykin A.G., 1987; Nekhoroshev A.S., Glinchikov V.V., 1990, 1991). Transaminase hepatic activity was changed significantly (Svidovy V.I. et al, 1985). Long term exposure has depressed hepatic microelement metabolism (ions of copper, iron, molybdenum, and magnesium) (Shvayko I.I. et al, 1984).

L.S. Nekhoroshev and V.V. Glinchikov (1991) has examined 60 matured male rats of ~ 250 g body weight. The exposure was tried at 8 and 16 Hz and 110 to 140 dB. The exposure duration was 5; 10; 15; 25 and 40 days, 3h/day.

At 8 Hz and 110-120 dB, the moderately expressed mosaic damage of hepatocytes has occurred. In secretion parenchyma, the diffuse changes of reactive processes in hepatocytes were observed. Changes were noted in sinusoids too.

The hepatocyte reaction was of mosaic character and accompanied by cellular damage with followed dissociation. This process has increased in case of longer exposure (5-10 days) and was specific to nuclei and cytoplasm changes. RNA cytoplasm content was increased and basophilic. Nuclei deformation was accompanied by chromatin redistribution and

concentration at nuclear membrane. In case 140 dB, hepatocyte changes were more expressed due to the cellular nuclei damage.

In changed hepatocytes, at days 1-5 of the exposure to 110-120 dB, the mitochondria enlargement has occurred with increased matrix density and crest deformations. Reticulum channels were expanded resulting to vacuole production. At days 25, 40, some hepatocytes have contained myelin-like bodies and lipid granules.

In case of 140 dB, nuclei deformed hepatocytes have degenerated. Polyblasts have concentrated around changed hepatocytes, which has resulted to infiltration. Proliferation processes were accompanied by large number of Kupfer cells, which were divided in mitosis and accumulated in the damaged parenchyma areas. The hepatocyte mitosis was observed in some cases, which has certified to regeneration.

At 16 Hz and 110-120 dB, both nuclei and cytoplasm were changed in hepatocytes. The nuclei deformation was the initial damage. Usually, such changes were observed within first 5 days of the exposure in dissociated cells. Simultaneously, such hepatocytes had cytoplasm changes (mitochondria enlargement with crest fragmentation). The endoplasmic reticulum was noted to have vacuole production with gradual decrease of ribosome count, lipid granule appearance and glycogen grain decrease. Vascular changes were also found: lumens were overfilled by blood and hemorrhage foci were observed.

In case of the infrasound exposure duration increase, the number of changed hepatocytes has increased; at days 10-15, degenerating hepatocytes were noted. Largest damage was found for 140 dB. In such case, the number of dissociated hepatocytes was increased.

Thus, at 8 and 16 Hz and 110-120 dB both intra-cellular membranes and mitochondrias are damaged. In case of 140 dB damaged hepatocytes have died. Less damaged hepatocytes have gradually recovered, though they have contained enlarged channels of endoplasmic reticulum and increased mitochondria density for a long period of time.

Changes described above and their expressiveness are most depended upon the exposure duration and sound pressure level; frequency ratio is less expressed.

Same authors (Nekhoroshev A.S., Glynchikov V.V., 1992) have examined infrasound effects in hepatic vascular system.

Experiments were tried in guinea pigs and white male rats. The exposure frequencies are 2, 4, 8 and 16 Hz and sound pressure levels are 90, 100, 110, 120, 130 and 140 dB. Single infrasound exposure was applied within 3 hours; multiple exposure was tried within 5, 10, 15, 25 and 40 days, 3 h/day. 10 animals were involved in each series (5 guinea pigs and 5 rats). Control was composed of 3 animals per each experimental series.

The single infrasound exposure at 90 dB has not induced any morphological changes in liver. At 100 and 110 dB the liver parenchyma was found to contain single fine hemorrhages and some dissociated hepatocytes. At 120 dB, the increase of arterial vessel diameters was noted as well as the capillary lumen expansion, which indicates to ischemia development. In ischemic sites, hepatocyte changes were revealed including expressed

cytoplasmic basophilia. Besides, some hepatocytes have been rounded and have lost inter-connections, which has resulted to partial decompensation of hepatic bars. In case of 130 and 140 dB, described changes were more expressed including increased hemorrhages and damaged hepatocyte number. At 8 and 16 Hz, damaged hepatocytes were present not only in ischemic areas but also in non-ischemic sites, which indicates to direct infrasound effect in hepatocytes.

Long time exposure of 5, 10 and 15 days has resulted to more expressed hepatocyte changes. Dissociated cells were usually round and smaller; strong basophilia was present. Diffused RNA concentration was elevated in changed hepatocytes. In case of 25 and 40 days exposure, the gradual death of changed hepatocytes was observed. The expressiveness of histological and histochemical changes was higher at 8 and 16 Hz, if compared to that at 2 and 4 Hz (for any time of the exposure), which can indicate to larger specificity of these frequencies in hepatic structure effects.

According to electronic microscopy, the single infrasound exposure of any tried parameters has not induced hepatocyte ultrastructure changes.

The multiple infrasound exposure has been found to show the exposure duration ratio for ultrastructure changes. For instance, in case of 5 day exposure, hepatocytes had the endoplasmic reticulum structure disturbance including membrane ruptures and ribosome death.

15 day exposure has induced more expressed ultrastructure changes in hepatocytes, which changes were of focal character. Hepatocyte nuclei were enlarged with peripheral shift of chromatin. Initial destruction signs were also the mitochondria enlargements with shorten crests and small vacuoles. Besides, damaged hepatocyte cytoplasm had increased ribosome count.

40 days exposure has induced large number of polymorph vacuoles with simultaneous decrease of mitochondria count in hepatocytes. Both rough and smoothed reticulum has disappeared. Cellular nuclei were significantly deformed and chromatin was concentrated at nuclear membrane. Such cells have not survived. Most expressed changes were observed 8 and 16 Hz if compared to that at 2 and 4 Hz.

Thus, most expressed histological, histochemical and ultrastructural changes were observed at 8 and 16 Hz.

The single infrasound exposure at 2, 4, 8 and 16 Hz and 90 to 140 dB (3 h duration) has not induced any hepatic changes of histological, histochemical and ultrastructural character. In case of multiple exposures within 5 to 40 days (3 h/day), most sensitive liver elements are hepatocytes. Hepatic changes are of focal character including ischemia sites, where hepatocytes are changed in structure or metabolism.

The short time infrasound exposure (5 to 15 days) has induced hepatocyte changes indicating to increased functional activity. Longer exposures (25 and 40 days) have induced irreversible hepatocyte changes.

Most expressed effects in hepatocytes were noted at 8 and 16 Hz. These data suppose to these frequency abilities to directly destroy cellular components and nuclei chromatin, which affects hepatocyte function.

These study results have justified the regulation of the infrasound sound pressure taking into account its frequency properties.

3.5 LFAO effects in blood system

The blood system is the most sensible one for any exposure. The blood system is important for non-specific and specific reactions including resistance and reactivity of the organism. Literature references indicate that LFAO effects in blood system are of the stress character.

It is known that different phases of adaptation relate to different counts of the white blood counts. At mobilization phase, leukopenia is usually noted. At this phase, the bone marrow is not significantly changed excluding mitosis activity depression. At resistance phase the counts of the blood and bone marrow are unchanged. In case of the long term exposure (exhaustion phase) the lymphocyte and eozinophil counts is decreased with the development of neutrophile leukocytosis.

N.F. Izmerov et al (1998) has examined white blood counts.

3 series were tried in Vistar male rats (180-250 g body weights). Each series has involved 12 control and 12 test animals.

Series I: 4 Hz and 130 dB; Series II-8 Hz and 130 dB and Series III-31.5 Hz and 130 dB. Examinations were done at hours 5, 25, 50 and 100 of the exposure and 2 weeks after the exposure termination. Peripheral blood reaction indicates to expressed effect.

Table 3.22 indicates that the exposure at 4 Hz and 130 dB (5, 25 and 50 hours) has resulted to the decrease of leukocyte count and partial recovery after 100 hour exposure. Besides, after 5 hour exposure, the confident (2 folds) increase of band neutrophile count was noted; after 50 hour exposure, almost double count of monocytes was noted. After - 100 hour exposure, ~ 2 times increase of band and segmented neutrophile count was found as well as monocyte count. It should be noted that lymphocyte count was decreased in case of 5, 50 and 100 hour exposures.

The observed picture indicates to the infrasound induced stress. The leukopenia reaction expressiveness indicates to the stress magnitude.

Table 3.22 - 4 Hz - 130 dB infrasound effects in white blood counts in rats (Izmerov N.F. et al, 1998)

Exposure duration, h	Animal group	White blood counts					
		Band neutrophils	Segmented neutrophils	Eosinocytes	Lymphocytes	Monocytes	(thousands)
5	control	1.5±0.29	33.0±4.14	1.33±0.36	63.2±4.42	3.3±0.47	19.23±1.7
	test	3.17±0.52*	32.0±2.78	0.58±0.19	60.2±3.50	4.1±0.95	15.2±2.2
25	control	1.7±0.39	23.3±1.98	1.30±0.37	72.8±2.13	2.4±4.30	20.59±1.94
	test	1.64±0.28	21.5±1.42	1.45±0.37	72.2±1.55	3.4±0.53	12.6±1.06*
50	control	1.5±0.26	21.9±2.54	2.17±0.35	72.1±3.03	2.67±0.49	21.56±2.02
	test	1.8±0.33	25.1±2.20	2.60±0.48	65.4±2.50	5.1±0.70	15.7±1.8*
100	control	1.08±0.36	17.5±1.66	1.92±0.38	77.08±1.85	2.3±0.67	14.73±1.74*
	test	2.8±0.59*	24.8±2.90*	2.10±0.38	66.6±3.14*	5.3±0.49*	24.1±2.8*

Note: * confident difference versus control

At all exposures at 8 Hz and 130 dB (Table 3.23), the confident lymphocyte count decrease was found (1.5-3.8 times); monocytes and segmented neutrophile counts were decreased after 25, 50 and 100 hour exposures as well as after 2 weeks of the recovery.

Table 3.23 - 8 Hz - 130 dB infrasound effects in white blood counts of rats (Izmerov N.F. et al, 1998)

Exposure duration, h	Animal group	White blood counts					
		Band neutrophils	Segmented neutrophils	Eosinocytes	Lymphocytes	Monocytes	(thousands)
5	control	2.0±0.59	27.6±2.4	1.5±0.25	70.4±2.0	1.36±0.28	17.9±1.5
	test	1.6±0.48	34.9±3.8	1.5±0.23	59.8±2.2*	5.1±1.10*	17.3±1.1
25	control	1.9±0.31	25.6±1.6	1.3±0.28	69.8±2.1	2.3±0.47	17.7±1.6
	test	1.9±0.47	36.6±3.77*	1.7±0.63	56.3±3.8*	5.8±0.59*	14.3±1.6
50	control	2.0±0.41	29.5±4.4	1.8±0.37	70.9±3.8	1.3±0.4	15.9±1.11
	test	1.8±0.39	39.7±2.5*	1.3±0.21	51.3±2.5*	6.2±1.4*	15.7±1.6
100	control	1.1±0.40	24.5±3.7	1.7±0.41	72.6±4.2	1.5±0.31	22.2±2.0
	test	2.7±0.40*	34.4±2.4*	1.9±0.34	57.7±2.9*	6.9±1.1*	16.3±1.7
2 weeks of recovery	control	1.6±0.43	20.5±2.5	2.3±0.52	75.5±2.9	2.0±0.62	22.1±2.1
	test	0.9±0.29	35.0±4.4*	2.5±0.59	63.3±4.4*	4.4±0.8*	22.1±2.6

Note: * confident difference versus control

After 100 hour exposure, the band neutrophile count was increased too. Total leukocyte count has not been changed. After 2 week recovery, the lymphocyte count was still decreased, whereas the monocyte and segmented neutrophile counts were increased.

At 31.5 Hz and 130 dB exposure within 25 hours (Table 3.24), the confident reaction was observed in monocyte count only.

The increased monocyte count was noted at all periods of the study. At recovery period, the change of white blood counts was found including leukocyte count decrease and segmented neutrophile count increase.

Thus, the exposure at 4 and 8 Hz and 130 dB has significantly shifted white blood counts. The leukopenia, monocyte count increase and white blood formula shift to the left were specific.

Table 3.24 - 31.5 Hz - 130 dB infrasound effects in white blood counts of rats (Izmerov N.F. et al, 1998)

Exposure duration, h	Animal group	White blood counts					
		Band neutrophils	Segmented neutrophils	Eosinocytes	Lymphocytes	Monocytes	(thousands)
5	control	0.4±0.20	28.8±2.4	1.5±0.37	69.6±2.86	1.2±0.39	15.5±1.2
	test	0.2±0.20	33.0±2.04	1.64±0.34	64.0±2.8	2.8±1.10	14.0±1.0
25	control	0.9±0.19	32.7±2.6	1.4±0.23	64.1±1.7	2.5±0.35	14.9±1.15
	test	1.1±0.40	36.2±2.4	1.92±0.42	59.8±2.9	4.0±0.60*	12.2±1.50
50	control	0.67±0.25	31.7±3.1	2.0±0.5	63.3±3.3	1.3±0.28	15.9±1.27
	test	0.3±0.19	31.6±2.3	1.5±0.31	68.6±1.4	2.45±0.5*	15.7±1.20
100	control	0.4±0.22	26.0±2.2	1.8±0.55	68.8±2.9	1.7±0.85	15.7±1.30
	test	0.3±0.20	32.0±3.0	0.83±0.21	66.9±3.5	3.6±0.85*	15.4±0.66
2 weeks of recovery	control	0.8±0.25	33.2±3.8	2.5±0.28	62.8±4.4	2.0±0.43	15.2±1.61
	test	0.11±0.10	38.9±1.16	3.2±0.64	51.7±2.8	3.9±0.06*	11.2±1.10*

Note: * confident difference versus control

In case of multiple exposures, some peculiarities were found. Changes are developed gradually within three periods of the adaptation syndrome. At the mobilization phase, the decrease of the lymphoid cell count and granulocyte count in the bone marrow is present. Peripheral blood count changes are not expressed at this phase.

Thus, at 4 Hz and 130 dB, the changes have reflected first phase of the stress.

When concerning monocyte peripheral count, P.D. Gorizontov et al (1983) have observed initial stress reactions.

Shifts of white blood counts induced by the infrasound were more expressed at 8 Hz and 130 dB if compared to that at 4 Hz. The lymphopenia, monocytosis and segmented neutrophile count increase were specific at this frequency.

At all examined exposure periods, the confident decrease of lymphocyte count, increase of monocyte and segmented neutrophile counts were noted for 25 hour exposure. After 100 hour exposure, the band neutrophile count was also increased. Total leukocyte counts have not been changed. After 2 week recovery, the lymphocyte count was still decreased and counts of monocytes and segmented neutrophiles were still increased. These changes have reflected the chronic stress reaction with stabilization of cell counts at decreased level. Apparently, such blood picture reflects transient resistance phase.

Thus, at 8 Hz, the shifts have reflected mobilization reaction and chronic stress for exposure periods of 25, 50 and 100 hours.

After 2 week recovery, the animals exposed at 8 Hz were not found to completely recover white cell counts. At 31.5 Hz, the confident reaction was observed for monocytes only. The increased monocyte count was noted for all examination periods excluding 5 hour exposure. At the recovery period, other white cell counts have been changed including leukocyte count decrease and monocyte count increase.

Thus, the comparative examinations of effects at 4, 8 Hz and 31.5 Hz and 130 dB have demonstrated that infrasound effects are more expressed than sound ones.

S.V. Alexeev et al have found changes of phosphorus lipid content of erythrocyte membranes and blood plasma albumin decrease (Alexeev S.V. et al, 1983). The significant increase of free and general cholesterol as well K+/Na+-ATPase activity in the blood serum has certified to the increase of erythrocyte membrane penetration (Alexeev S.V. et al, 1984; Kolmakov V.N. et al, 1984; Svidovy V.I. et al, 1987; Melkonyan M.M., 1989). The succinate dehydrogenase, alanine- and asparthate amine transferase activity increase has reflected the increase of oxidative and transaminase activity increase in liver and myocardium. In vitro control tests have demonstrated unchanged concentrations of these enzymes (Svidovy V.I. et al, 1985; Svidovy V.I., Sleykin A.G, 1987).

S.V. Alexeev, V.N. Kolmakov, and V.I. Svidovy (1984) have examined LFAO effects in isolated erythrocytes.

Tests were tried in conserved human erythrocytes separated from liquid blood residuals and conservancy. The exposure was tried at 2 Hz - 90 and 110 dB, 4 Hz - 100 and 125 dB, 8 Hz - 100 and 140 dB (1.3 or 6 h exposure).

Results are provided by Table 3.25.

Confident decrease of the erythrocyte membrane penetration was found in case of 3 h exposure (upper part of hemolysis curve). Apparently, this effect is related to changes of albumin components of membranes.

Table 3.25 - Changes of erythrocyte membrane penetration (EMP) in case of 3 h LFAO exposure at different frequencies and intensities

The ratio of isotonic solutions of urea/sodium chlorine	2 Hz			4 Hz			8 Hz		
	control	90 dB	110 dB	control	100 dB	125 dB	control	100 dB	140 dB
65:35	99.3	95.0 <0.01	92.5 <0.01	91.0	94.	92.0	96.8	95.3	94.9
60:40	95.8	87.8 <0.01	87.3 <0.01	84.4	87.7	85.9	91.3	88.8	87.8
55:45	72.7	62.1	64.7	74.5	74.9	74.8	74.5	66.5	69.2
50:50	35.8	31.7	29.1	51.0	49.5	54.0	40.5	41.7	35.6
45:55	18.2	15.0	14.1	32.0	28.2	37.1	20.4	16.1	14.2

The clear frequency ratio was noted: 4 Hz oscillations do not affect the membrane. For 1 h exposure EMP changes were unconfident; they were more expressed in case of 3 h exposure. Short time exposure has induced different directions of EMP changes: decrease or increase ($p<0.05$). Such effect was noted by V.V. Sokolovsky et al (1977).

The clear frequency ratio was noted for EMP effects. At 2 Hz and 90 dB, EMP is increased (2767 conditional units in control versus 3751 conditional units in experiment, $p<0.01$). This finding indicates to membrane destabilization. In case of 110 dB, EMP is increased (2702 conditional units in control versus 4131 conditional units in experiment, $p=0.01$); simultaneously, some tests have provided paradoxical effect (2985 conditional units in control versus 2226 conditional units in experiment,

p=0.05). it can be explained by the depression of rhythmic changes of the membrane penetration apparently related to LFAO induced depression of cellular activities. At 4 Hz, minimal EMP changes were noted (3196 conditional units in control versus 3107 conditional units in experiment in case of 100 dB intensity). In case of 125 dB, the penetration is changed to 4172 conditional units (p=0.01). At 8 Hz, in 12 tests the penetration was increased from 2750 to 3687 conditional units (p<0.05) for 100 dB; in 9 tests the paradoxical effect was found: the penetration decrease from 4674 to 3265 conditional units (p=0.05). In case of 140 dB, in 12 tests the penetration has increased from 2786 to 4080 conditional units (p=0.01); in 9 tests it has decreased from 4628 to 3056 conditional units (p<0.05).

The results of this study indicate that LFAO effect mechanism is significantly determined by initial damage of structure and function of cellular membranes. It can be supposed that this conclusion is valid for both erythrocytes and other cells.

S.V. Alexeev et al (1984) studies were prolonged by V.N. Kolmakov et al (1984), who have analyzed the components of membranes under the effect.

Following indices were examined: erythrocyte acetyl choline esterase, erythrocyte catalase, and general cholesterol. LFAO exposure parameters were as follows: 2 Hz - 90 and 110 dB, 4 Hz - 100 and 125 dB, 8 Hz - 100 and 140 dB. Exposure time was 3 hours.

The cholesterol tests have not revealed confident changes. The labile/general cholesterol in erythrocyte membranes was found to be 0.18±0.02 in control (n=62); it was changed in case of the exposure at 2 Hz, 90 and 110 dB (0.20±0.03 and 0.20±0.02, respectively), and at 4 Hz and 100 and 125 dB (0.16±0.03 and 0,18±0.03 respectively). However, at 8 Hz and 100 dB, this value was confidently changed (0.32±0.04) versus control (n=31, t=3.13, p<0.02). Similar results have been observed at 8 Hz and 140 dB: labile/general cholesterol ratio of 0.29±0.04 (n=29, t=2.45, p<0.02).

The results demonstrate that low frequency acoustic oscillations are able to destabilize erythrocyte membrane structure (labile/general cholesterol ratio increase in erythrocyte membranes); this effect is significantly dependent upon the frequency (it was found at 8 Hz and was absent at 2 and 4 Hz). The intensity ratio is less expressed.

LFAO have affected erythrocyte ferments. The catalase activity was affected at all examined frequencies. Different character of changes has required the group analysis applying pairs in dependent totalities (Table 3.26).

The different directions of found changes of catalase activity result to poor applicability of this parameter to detect LFAO effects.

Quite different results were obtained for LFAO effects in acetylcholinum esterase (ACE) activity in erythrocytes (Table 3.27).

ACE activity changes are frequency dependent. At 2 Hz, the confident ACE activity increase was noted. The intensity increase from 90 to 110 dB is accompanied by confident activation effect increase.

At 4-8 Hz, the ACE depression is noted and it is confidently decreased for 140 dB. However, it is important to note that ACE is the membrane related ferment, so its activity change can be induced by both the direct effect and to the change of its membrane interaction. Clear ACE activity

changes for relatively low intensity (90 dB) indicate to possible application of this index for LFAO effect investigation.

Table 3.26 - Catalase activity changes (in mM of dissipated H_2O_2 per minute per 1 ml erythrocyte cloud) in case of LFAO exposure

Index	LFAO parameters					
	20 Hz 90 dB	4 Hz 100 dB	8 Hz 100 dB	2 Hz 110 dB	4 Hz 125 dB	8 Hz 140 dB
Baseline level	2135 (3675–865) n = 10	3310 (5150–1935) n = 11	2310 (3675–865) n = 12	1810 (3675–565) n = 12	3810 (5759–2430) n = 10	2970 (3675–1835) n = 10
Decrease after exposure	1755 (3285–865) P = 0.01	2730 (3840–1865) P = 0.01	1715 (2530–530) P = 0.05	1435 (2665–400) P = 0.01	2560 (3900–1500) P = 0.05	1740 (2305–655) P = 0.01
Baseline level	1305 (565–2280) n = 9	2840 (1300–4650) n = 7	1145 (565–1760) n = 9	1525 (865–2280) n = 6	2915 (1300–4650) n = 11	1195 (565–2200) n = 11
Increase after exposure	1995 (1100–2600) P = 0.01	3955 (1970–5500) P = 0.01	1745 (1000–2560) P = 0.01	2075 (1445–2470) P = 0.01	3954 (1695–6200) P = 0.01	1450 (730–2325) P = 0.01

Note: Catalase activity range is given in brackets.

Table 3.27 - ACE activity changes induced by LFAO exposure

Experimental conditions	No. of tests	ACE activity, ncat/ml	T	p
Control	13	255±23.5	—	—
LFAO at:				
2 Hz 90 dB	11	334±12.8	2.94	<0.01
2 Hz 110 dB	11	388±17.2	4.56*	<0.01*
4 Hz 100 dB	10	207±20.3	1.54	>0.05
4 Hz 125 dB	10	199±17.5	1.91	>0.05
8 Hz 100 dB	11	205±19.2	1.64	>0.05
8 Hz 140 dB	11	174±8.4	3.24	<0.01

*Note: * Between 2 Hz, 90 dB and 2 Hz, 110 dB: T = 2.51, p = 0.02*

Basing upon examination results, it was concluded that changes of some biochemical parameters of erythrocytes depend upon the exposure frequency; LFAO intensity ratio is less expressed for these changes.

3.6 LFAO effects in microelement metabolism

The infrasound effects in microelement metabolism were considered by one publication of I.I. Shvaiko et al (1984).

Earlier studies (Gabovich R.D. et al, 1979; Sanova A.G., 1977; Shutenko O.I. et al, 1979) have established that infrasound affects breath function, nervous and sympathetic adrenal system functions. It was supposed that infrasound directly affects intra-cellular membranes, which results to disturbances of biological oxidation and oxidative phosphatation; the corticosterone plasma content is increased in adrenals, which is related to long term stimulation of the sympathetic adrenal system.

I.I. Shvaiko et al (1984) have examined effects of the long term infrasound exposure of different intensity in animal metabolism of microelements (copper, molybdenum, iron, magnesium).

White male rats (185±6 g initial body weights) were exposed within 4 months (2 h/day) at 8 Hz and 90 dB (group 2), 115 dB (group 3) and 135 dB (group 4); group 1 was the control.

The microelement balance was examined at the end of months 1 and 4. Animals were kept in metabolism cages to collect urine and feces within 5 days. at the end of experiment the postmortem analysis was tried. The contents of copper, molybdenum, iron, and magnesium were evaluated applying quantitative spectrography (ISP-28). Microphotometer (MF-2) was used to decode spectrograms. The logarithmic scale etalon was used to assess microelement quantities. The results were confident for $p<0.05$.

For 135 dB, the copper content in excreta was decreased for 12.3 % versus control; for 115 dB it was decreased for 7.7%; for 90 dB, this index was unchanged.

The copper content analysis (Table 3.27) in organs has revealed confident ($p<0.05$) increase in liver (for 18.9 %), brain (111 %), skeleton muscles (79%) and decrease of this element in spleen and bones (for 25.6 and 45 %, respectively) in group 4 animals. Similar but less expressed changes were noted for 115 and 90 dB.

Table 3.27 - Microelement content in rat tissues after 4 month exposure at 8 Hz (M±m)

Object	Animal group			
	1 (control)	2 (135 dB)	3 (115 dB)	4 (90 dB)
Copper, μg %				
Liver	495.6±48.1	813.6±81.0*	589.3±58.0	603.1±60.0
Spleen	196.4±20.0	98.2±9.7**	113.5±10.7*	145.8±14.6
Brain	211.4±21.1	445.6±44.2**	182.5±18.0	211.4±21.2
Skeleton muscles	20.5±2.0	36.7±3.7**	27.6±2.7	19.6±2.0
Bones (femoral)	425.6±53.4	234.3±33.2*	421.7±41.7	425.6±52.6
Molybdenum, μg %				
Liver	51.7±5.2	28.2±2.8**	39.5±4.0	43.9±4.4
Spleen	5.8±0.6	7.0±0.7	6.5±0.6	6.3±0.6
Brain	6.8±0.7	3.4±0.3**	4.5±0.4*	4.5±0.4*
Skeleton muscles	2.3±0.2	3.7±0.4*	3.4±0.3*	3.0±0.3
Bones (femoral)	979.6±95.4	1293.5±130	1104.6±110	1021.5±101
Iron, mg %				
Liver	16.8±2.0	39.3±4.0**	29.2±3.0*	21.2±2.1
Spleen	13.3±1.4	9.4±0.9	10.1±1.0	12.2±1.2
Brain	14.0±1.1	21.3±2.2*	18.9±1.7*	16.6±1.4
Skeleton muscles	2.9±0.3	5.5±0.5**	5.0±0.5*	3.4±0.3
Bones (femoral)	32.7±3.3	18.4±1.8**	19.7±2.1*	23.3±2.1
Magnesium, μg %				
Liver	169.4±17.0	357.4±35.6**	226.0±22.5	214.9±21.5
Spleen	13.1±1.2	26.7±2.7**	25.3±2.4*	24.4±2.4**
Brain	25.0±2.4	37.6±3.8*	27.7±3.0	27.7±3.0
Skeleton muscles	5.8±0.6	19.9±2.0**	7.0±0.7	6.9±0.7
Bones (femoral)	54.1±5.5	83.4±8.3*	64.1±6.6	61.7±6.2

Note: * $p < 0.05$, ** $p < 0.01$.

The confident molybdenum excretion decrease was also noted. It was most expressed in group 4 rats (135 dB). Changes of inter-organ re-distribution were of alternative character. The molybdenum decrease was found in liver and brain in all exposed groups ($p<0.05$) (in group 4 it was 45.5 and 50 %, respectively); it was increased in spleen, muscles and bones (for 20.7, 60.2 and 32 %, respectively). This finding indicates to some antagonism of copper versus molybdenum and their significance in infrasound induced changes of metabolism.

Infrasound has changed the iron metabolism. In group 4 (135 dB), the confident ($p<0.05$) increase was noted in liver (for 133,9 %), brain (for 52.1%), skeleton muscles (for 89,7%); the decrease was found in spleen and bones (for 29.3 and 43.7%, respectively). in groups 2 and 3, same changes were less expressed. Thus, the copper and iron metabolism are synergetic, which apparently indicates to their role of metal components involved in blood system and hemopoiesis. These changes are compatible to the breath changes found by A.G. Sanova (1977).

All animal groups were observed to have the expressed excretion decrease of magnesium (for 47.7 and 64.3 % versus control) and its accumulation in the body. It is certified by organ burden increases as follows: for 110 % (liver), for 103.8 % (spleen), for 50.4 % (brain), for 243.1 % (skeleton muscles), for 54,2 % (bones). In groups 3 and 2, this increase was confident ($p<0.05$) in liver (for 33.4 and 26 %, respectively) and in spleen (for 93.1 and 86.3%); other organs were noted to have magnesium increase trend.

Described changes of copper, molybdenum, iron, magnesium metabolism are possibly important for adaptive compensatory reactions to the infrasound exposure and related to functional disturbances in nervous and sympathetic adrenal systems with increased catecholamine release to the blood (Shutenko O.I. et al, 1979).

Data certify to the convenience of future research to clarify infrasound induced changes of microelement metabolism including microelement balance examination in humans exposed to the industrial infrasound to determine ways to normalize balance and body distribution of microelements.

3.7 LFAO effects in endocrine system

Many studies have demonstrated that endocrine system is important for adaptation to the harmful environmental factors and for the induced pathological change progress. At the same time, despite the significant amount of studies devoted to LFAO effects, the endocrine system effects are not practically investigated and the existing studies reflect only some parts of the endocrine regulation. Besides, these studies are usually devoted to the short time exposure.

LFAO at 2-63 Hz and 100-145 dB have induced the decrease of neurosecretory nuclei in hypothalamus, which has certified to the activation of releasing factors and tropic hormones of the hypophysis (Yaglov V.V. et al, 1987). The increased concentration of these hormones has resulted to the blood content increase of thyrosinum, catecholamines and corticosteroids (Paranko N.M., Madatova R.B., 1990).

The significant change of endocrine system activities was of expressed phasic character (Yaglov V.V. et al, 1987). Significant catecholamine level changes (Paranko N.M., Madatova R.B., 1990) and blood plasma acetylcholinum change (Alexeev S.V. et al, 1980), which were of different directions at different terms of LFAO stimulation, were found. At the same time, in case of the long term exposure, the corticosteroid concentrations were elevated (Gabovich R.D. et al, 1979) as well as the acetyl choline esterase (Kolmakov V.I. et al, 1984). The combination of revealed immune reactions (see section 5.4) with changed activity of sympathetic adrenal system has certified to the compensatory adaptive reaction activation in case of the LFAO exposure.

Together with blood hormone level change, the low frequency acoustic oscillations have also induced humoral tissue factor increases in the microcirculatory basin, which has affected the endothelium penetration regulation and local vascular blood flow velocity (Dzizinsky A.A., Gomazkov O.A., 1976; Dotcenko V.L. et al, 1989). Different animal species exposed to LFAO were found to have changes of the blood content of local vascular regulation factors including histamine, acetylcholinum (Shutenko O.I, et al, 1979) and bradykinin (Ponomarenko G.N., 1994).

V.O. Samoilov et al (1994) have examined the pre-callycreine and callycreine activity in the blood plasma (as well as the quininease (carboxypeptidase N) activity) applying spectrophotometry techniques with different substrates (Eliseeva Yu.E. et al, 1976; Dotcenko V.L. et al, 1982). Anti-trypsinum ability of the blood plasma was assessed via levels of α_1-anti-trypsinum and α_2-macroglobulin.

Activities of these substances were examined applying unified spectrophotometry technique similarly to the general blood plasma albumin.

LFAO have induced the expressed elevation of callycreine-quinine system activity in the blood plasma. Study results are provided by Table 3.28.

The results certify to the fact that LFAO induces active and pre-callycreine production in rats. It is confirmed by the decrease of pre-callycreine content and confident ($p<0.05$) increase of callycreine in all animal groups exposed to different LFAO intensities. Therefore, low frequency acoustic oscillations activate serumal proteases of the blood plasma.

Table 3.28 – Callycreine-quinine system components and blood plasma albumins in rats exposed to LFAO (Samoilov V.O. et al, 1994)

Parameters	Content of:					
Frequency, Hz; PFD, $mW \cdot m^{-2}$	pre-callycreine, $mU \cdot mL^{-1}$	callycreine, $mU \cdot mL^{-1}$	quininease, $n \cdot 10^{-3}$ $mU \cdot mL^{-1}$	general plasma albumin, $mg \cdot mL^{-1}$	α_1-anti-trypsinum, $CU \cdot mL^{-1}$	α_2-macro-globulin, $CU \cdot mL^{-1}$
Control	165 ±26	22±2	102±4	54.5±1.9	27.7±2.4	4.2±0.8
33; 1	143±16*	33±2	118±4	58.4±1.6	31.2±1.7	4.2±1.8*
63; 1	145±21*	44±2	145±8	54.2±1.9*	32.9±2.4	3.0±1.7*
63; 250	128±18	48±2	128±4	54.3±1.8	30.7±1.6	3.0±1.3*
100; 1	136±18*	30±3	119±8	56.3±1.4*	28.6±1.5*	3.6±1.2*
100; 250	136±16*	33±2	118±5	60.0±1.6	29.8±2.7*	4.3±1.6*

Note: * – unconfident difference versus control (P>0.05).

The increase of protease activity is able to change vascular penetration and functional properties of propryoreceptors.

The increased proteolytic ability of blood plasma was compensated by the anti-protease activity increase. The ciantitrypsinum level has been significantly ($p<0.05$) increased in the majority of cases, whereas the α_2-macroglobulin activity has increased insignificantly or was decreased in some cases. Such decrease of polyvalence protease inhibitor activity could be related to the production of non-active complex of α_2-macroglobulin-protease (Veremeenko K.N. et al, 1988). At the same time, the macroglobulin deficiency has not resulted to significant change of protease/inhibitor ratio. The increased protease content has been counterpoised by the increase of anti-trypsinum ability of the blood plasma. It should be noted that this effect has been revealed only for long term (~ 15 min) LFAO exposure.

The power flux density increase has resulted to the increase of callycreine content in the blood plasma (63 Hz). Besides, the increase of anti-trypsinum activity was not found. The data on increased activity of serumal proteases confirm results obtained for microcirculatory basin, which results certify to local blood flow change in case of the elevated power flux density (Karpova N.I., Malyshev E.N., 1981).

The involvement of bradyquinine and other active quinines in LFAO effect realization are confirmed by confident changes of the blood plasma quinine activity (Table 3.28). The quininease level was increased in exposed animals. Such activity increase of quinine hydrolysis ferments is, apparently, of compensatory character and represents the response to the callycreine content increase.

The callycreine-quinine system components are sensitive to LFAO exposure. At the same time, applied acoustic exposure has not induced significant albumin changes. Apparently, other non-specific systems (albumin synthesis, particularly) are less sensible to the investigated factor.

Thus, low frequency acoustic oscillations have induced the equilibrium disturbance of activating and inhibiting components of callycreine-quinine system. The increase of callycreine activity and decrease of its inhibitors has happened. The activation of quinine producing enzymes results to the compensatory elevation of quinine hydrolyzing ferments (Ponomarenko G.N., 1994).

V.V. Yaglov et al (1987) have analyzed morphological functional state of basic parts of the endocrine system in case of the long term LFAO exposure.

Experiments were tried in 160 Vistar male rats. Animals were exposed to 130 dB and 4, 8 and 31.5 Hz (5 h/day). Animals were sacrificed at days 1.5, 10 and 20 of the exposure and at the end of 2 week recovery period. The histological examination of large nuclei of hypothalamus (supraoptical (SON) and paraventricular (PVN) ones, hypophysis, adrenals, thyroid and semens.

At 4 and 8 Hz, the systemic reaction was of phasic character. Single exposure results to the expressed reaction. In SON and PVN, the portion on neurons of types I and II is increased. The number of axon enlargements is increased. The neurosecretion concentration is decreased in the rear hypophysis. Simultaneously, the neurohypophysis hyperemia was noted, which indicates to intensive neurohormone resorption in the blood basin. In case of the exposure time increase at 4 and 8 Hz, the HHNS activation signs are less expressed. Particularly, SON and PVN are specific to the increased number of type III cells overfilled by neurosecretion granules. At the same time, the neurohypophysis deposited material amount is increased and has reached the control level at day 10 (4 Hz). At day 20, the neurosecretion concentration is above control indices. At the end of the recovery period, all parts of HHNS have been similar to the control ones. At 31.5 Hz, confident shifts were not found in SON and PVN cells as well as in neurosecretion content in the rear hypophysis.

In the adenohypophysis, LFAO exposure at different frequencies has induced structural changes specific to the alarm of general adaptation syndrome, which were most expressed at 8 and 31.5 Hz. In case of the multiple LFAO exposure the changes are reduced at the tissue level.

Signs of adrenal cortex activation were only found at the beginning of LFAO exposure at 4 Hz. After 10 days of the exposure, this index is gradually decreased and returned to the initial level (see Table 3.29). Histological structure is changed: vascular enlargement and erythrocyte stasis are present. The lipid distribution is of mosaic character. All these phenomena were also observed at 8 and 31.5 Hz; their expressiveness is increased with the increase of frequency and exposure time. At 8 and 31.5 Hz, the width of the fascicular zone is not changed until day 5; thereafter, it is decreased and persists to be decreased within the whole recovery period.

The system of hypophysis - thyroid is observed to have some dissociation of hypophysis function and peripheral compartment, however, changes are less expressed. Adenohypophysis β-basophils state certifies to the moderate increase of the thyroidal function in all experimental animals. The thyroid morphology indicates to its secretion activity increase after the single exposure only (see Table). After 5 day exposure, the increased thyroid function was noted only for 4 Hz. At 10 day, morphological indices have indicated to the absence of the thyroidal changes. Depression signs were

noted at the end of the exposure but have disappeared at the end of the recovery period.

The hypophysis-gonads system was found to be affected by LFAO at 4 Hz; initially, the degranulation of gonadotropocytes in adenohypophysis and spermatogenesis activation were noted within first 5 days of the exposure (see Table). Later on, gonads were found to have hemodynamics disturbances, interstitial edema and progressing decrease of generative and hormone producing function. Simultaneously, the number of castrated cells is increased in hypophysis with maximum reached at the end of the recovery period. At 8 and 31.5 Hz, the generative function decrease was noted after the first exposure on the background of expressed vascular disturbances. Simultaneously, the atrophy of interstitial cells producing androgens is developed.

Table 3.29 - Quantitative indices of adrenals, thyroid and semens in case of the LFAO exposure of 130 dB

Exposure duration, hours	Frequency, Hz	The width of fascicular zone of adrenal cortex, μm		Volumetric portion of the thyroidal colloid, %		Number of spermatogonias per one cross-section of gyrose channel	
		test	control	test	control	test	control
5	4	438±24.2*	380±14.3	28.6±1.1*	33.0±0.6	59.4±1.3	57.9±3.0
	8	439±11.1	443±18.7	22.8±1.3*	26.2±1.0	52.4±1.6	57.3±1.8
	31.5	462±20.9	441±9.9	23.8±0.5*	29.5±1.2	52.9±1.3	60.1±0.6
25	4	408±15.4	382±20.7	26.6±2.8*	35.1±2.2	54.6±0.9*	48.4±0.6
	8	484±18.7	500±6.6	24.0±2.4	23.6±1.1	50.3±1.0*	56.1±1.2
	31.5	551±41.8	525±37.2	33.0±0.8	35.4±1.2	49.5±1.7*	57.2±1.1
50	4	418±25.3	479±22.0	31.5±3.1	31.2±2.4	50.3±1.6*	59.9±0.6
	8	389±25.3*	485±16.7	25.6±1.6	26.8±2.2	48.3±0.9*	57.1±1.2
	31.5	409±14.3*	556±32.8	30.7±2.3	30.0±1.3	49.0±1.7*	62.5±0.6
100	4	408±9.8*	499±18.7	41.3±1.7*	33.6±1.7	49.0±0.8*	61.1+1.0
	8	358±23.1*	540±8.8	22.2±2.9	25.2±2.5	48.5±0.8*	55.1+1.0
	31.5	448±39.6*	534±11.0	33.8±1.6*	27.8±1.2	50.0±1.2*	62.1+1.0
2 weeks of recovery	4	421±11.0*	495±7.7	27.1±1.9	29.9±1.5	47.1±0.9*	60.6±2.1
	8	388±25.3*	532±14.3	26.6±2.0	24.7±0.6	-	-
	31.5	449±19.8*	525±24.0	29.0±3.4	32.5±0.4	47.8±2.2*	60.3±0.9

Note. Asterisk indicates confident differences

The increase of LFAO exposure time results to the decrease of spermatogonia and this process is prolonged after the exposure termination. At this period, the secretion activity of gonadotropocytes is maximal; more that 12% of these cells is transformed to castration cells.

The LFAO exposure of 130 dB has induced expressed changes of the whole endocrine system. HHNS changes are of phasic character. The expressed activation of all endocrine compartments after the single exposure is certainly of compensatory significance. The stabilization of the system state in case of the increased exposure time is supposed to the fact that produced neurohormones (ADH and oxytocine) do not affect hemodynamic disturbances. Vascular disorders and tissue hypoxia are the specific effects of LFAO exposure of high intensity. Apparently, this is the cause of the atypical reaction of hypophysis - adrenal cortex system reaction to LFAO. Signs of dysfunction and cortical exhaustion were revealed in adrenals on the background of corticotropocyte activity increase. The depression of adrenal cortex function was also observed in case of the long time exposure to noise and general vibration. Thus, this sign makes LFAO effects similar to the effects of local and general vibration. The thyroidal

functional and morphological changes are also similar to that resulted from general vibration rather than to audible noise effects.

The expressed LFAO induced depression of reproductive and endocrine functions of semens was revealed. Thus, the long term LFAO exposure indicates to the critical character of gonad function decrease. The examination of adrenal cortex and gonad state would be the informative test to assess the LFAO effects in the organism.

Authors have concluded that the change of the state of hypothalamus-hypophysis-neurosecretion system in case of LFAO exposure at 4, 8 and 31.5 Hz and 130 dB is of reversible character: short time activation is followed by normalization. The thyroid reaction is specific to initial increase and followed decrease of functioning level. The revealed changes of hypophysis-adrenal cortex and hypophysis-gonads systems are specific to the persistent hypofunction of peripheral compartments and to the amplification of tropic adenohypophysis functions.

3.8 LFAO effects in nervous system

The LFAO of > 110 dB has induced the cerebral cortex excitation (Petounis A, et al, 1978; Mozhukhina N.A., 1979; Alexeev S.V., Usenko V.R., 1988).

The disseminated character of vegetative nervous system center excitation was considered to be the cause of multiple and variable CNS reactions as well as reactions of cardiovascular and respiratory systems (Broner N., 1978; Landstrom U., 1983). LFAO exposure at 10, 15 and 20 Hz and 130-140 dB has transformed θ-rhythm in rabbits. The β-rhythm was dominated (Mozhukhina N.A., 1979; Petounis A. et al., 1977). Followed increase of SPL to 170 dB (3-20 Hz) has amplified bioelectric cerebral activity, its synchronization and acceptation of LFAO rhythm (Bachurina T.I., 1974). Bioelectrical cerebral activity changes were increased with power flux density increase (Bachurina T.I., 1974; Petounis A. et al., 1977; Mozhukhina N.A., 1979).

Because of clear selectivity of the whole body reactions (Gierke H. von, 1964, 1974) (see Chapter 4), the peculiar interest was attracted to the experimental examination of LFAO synchronization with basic bioelectrical cerebral rhythms. It was supposed that these oscillations can be transformed into electromagnetic ones (acoustic effect of the second kind) and "imitate signals of the internal communication between cortex neurons". In case of the coincidence of acoustic-electric oscillations with cerebral bioelectric rhythm, the oscillations would became cophased and their amplitude could be superposed (Mirkin A.S., Lubimova G.V., 1989). In such case, 7 Hz would be most harmful for human because of coincidence with cerebral bioelectric activity rhythm (Gavreau V., 1968; Andreeva-Galanina E.Tc. et al, 1970; Johnson D.L., 1974; Arabadji V.I., 1992).

The experimental test has demonstrated that this supposition was erroneous: confident α-rhythm changes were not found in case of 7 Hz exposure (Petounis A. et al., 1977; Stanley H.C., Johnson D.L, 1978; Karpova N.I. et al, 1979; Mozhukhina N.A., 1979; Karpova N.I., Malyshev E.N., 1981; Mozhukhina N.A., Alexeev S.V., 1983).

In some rabbit experiments, the synchronization of Δ- and θ-rhythms was revealed in reticulum and hyppocampus at 18 and 29 Hz and 105 and 115 dB (Utemisov B.K., Nurbaev S.K., 1988). In such case, the θ-rhythm synchronization could reflect unconditioned orientation reflex rather that frequency dependent specific reaction (Karpova N.I. et al, 1979; Mozhukhina N.A., 1979). Some Δ-rhythm amplification, apparently, was the consequence of hypernoae and cerebral hypoxia induced by LFAO (Bachurina T.I., 1974). The detailed EEG analysis in case of LFAO exposure of low intensity has demonstrated that the frequency selectivity of bioelectrical cerebral processes is poorly expressed (Petounis A. et al, 1977; Mozhukhina N.A., 1979).

The modern understanding of the bioelectrical cerebral activity excludes considerations of low frequency resonance of oscillating processes of different nature. Despite of changes of nervous center functional properties in spinal cord and brain neurons, the central and peripheral chromatolysis (Sudzilovsky F.V. et al, 1974), focal cortical ischemia and mild meninx edema were revealed (Nekhoroshev A.S., Glinchikov V.V., 1991). Decreased oxygen consumption in cerebral tissues was demonstrated (Shutenko O.I. et al, 1979).

Provided results suggest that LFAO exposure is responded by the whole organism including nervous, cardiovascular and respiratory systems. Within two recent decades, the attention was attracted to the ratios of LFAO effects versus the exposure parameters. The trend of the effect increase in case of the sound pressure elevation is clear in recent studies (Suvorov G.A., 1968; Gabovich R.D. et al, 1979; Shutenko O.I. et al, 1979; Alexeev S.V., Usenko V.R., 1988; Nekhoroshev A.S., Glinchikov V.V., 1991).

The grade of organ and tissue damage has increased in case of prolonged LFAO exposure. Several phases of reactions were observed, which could be the signs of adaptation and tension in correspondent regulatory compensatory systems (Karpova N.I., 1979). At days 10-15 of the exposure, the animals were observed to have the amplified regeneration together with damage signs, which regeneration was most expressed at day 30 (Yakubovich T.G., Polyakova T.I., 1979; Bobyleva N.A., 1990). At that time, cerebral and cardiac bioelectric processes have also stabilized in rabbits (Mozhukhina N.A., 1979; Alexeev S.V., Mozhukhina N.A., 1983).

The important research direction is the frequency ratio of LFAO effects in case of high intensity of the exposure. Despite of many

attempts, the clear frequency ratio was not found for LFAO exposure at 2-100 Hz (Broner N., 1977; Mozhukhina N.A., 1979; Karpova N.I., Malyshev E.N., 1981; Paranko N.M., Madatova R.B., 1990; Nekhoroshev A.S., Glinchikov V.V., 1991).

At present time, the convinced evidences of expressed frequency selectivity were not obtained for LFAO effects. Following conclusions can be drawn from failed attempts to prove this frequency selectivity.

Firstly, resonance frequencies are determined by the mechanical impedance of the human body and depended significantly upon the muscular tone (Pimonow L., 1976; Kreymer A.J., 1986; Binder M.D., 1986; Stoma M.F., 1988). Frequency ratios of specific frequency impedance are individual and depend on the body mass, body sizes and physical peculiarities of LFAO exposure (Gierke H.E. von, 1974; Brankov G., 1981). The low quality factor of biological oscillation systems supposes the presence of unclear maximums of resonance curves, which was experimentally established (Alexander R., 1970; Tarnoczy T., 1974; Arabadji V.I., 1992).

Secondly, it is obvious that it is necessary to investigate frequency ratios of effects in different physiological systems rather than mechanical resonance resulted from the coincidence of linear sizes and wavelength (Romanov S.N., 1983, 1991). Apparently, it is the reason of the finding where the LFAO exposure at frequencies of internal organ resonance has not significantly affected the organ functions (Broner N., 1978).

Thirdly, incorrect experiment arrangements are noted in some instances. The examination of resonance frequencies was elaborated via integral index assessment like pulse rate or breath rate, which magnitudes are determined by the combined activity of a number of inter-related regulatory mechanisms (Broner N., 1978; Karpova N.I., Malyshev E.N., 1981; Romanov S.N., 1991). Resulting frequency ratios did not have expressed extremums.

Obtained results have confirmed the possibility to affect biological objects. At the same time, the majority of recorded phenomena were also found in case of the low frequency vibration (Broner N., 1978; Artamonova V.G., Shatilov N.N., 1982; Stoma M.F., 1988; Alexeev S.V. et al, 1991) and intensive high frequency sounds (Kryvitskaya G.N., 1964; Nychkov S., Kryvitskaya G.N., 1969).

The comparative analysis of recorded reactions has not revealed *specific* peculiarities of LFAO health effects in case of their significant intensity. These effects are manifested via *damage and destruction* of tissues, which results to the irreversible deformation of cellular structures. The attempts to understand LFAO effects mechanisms are predominantly the systematization of changes of most general homeostasis parameters, which are apparently *non-specific* and can reflect the response to *any* physical factor of high intensity. LFAO health effects in case of the low intensity, apparently, are determined by selective *sensitivity*

of different biological structures including mechanical sensorial systems.

Principally, low frequency acoustic oscillations can affect any cell of the organism. However, in case of low intensity, the high sensible sensorial systems are most important. The assumption of CNS neuron sensitivity to LFAO exposure is not reprehensible. But this assumption diminishes the importance of sensorial systems, which are much more sensible than any other body structures. Being the kind of peculiar amplifiers, the sensorial systems form cooperative processes to provide reactions which energy output is much higher than the applied exposure energy. The only thing to be proved is the assumption that low frequency acoustic oscillations are the adequate stimulation of different mechanical receptors; the conditions and peculiarities of their responses and information flows from mechanical receptors of different types have to be established. It is the necessary condition to justify the new viewpoint consisting in the mechanical receptor perception of low frequency acoustic oscillations.

3.9 LFAO effects in vision organ

The vision organ perceives ~ 90 % of the whole environmental information. The Russian literature contains only two papers on the unfavorable effects of noise and infrasound in the vision organ (Svidovy V.I. Kuklina O.I., 1985 and Kosacheva T.I., Svidovy V.I., Alexeev V.N., Kovalenko V.I., 2001).

1985 study was tried in matured white male rats exposed to 8 Hz, 100 and 140 within 5, 10, 15, 25 days (3 h/day). Each series was composed of 10 animals including 3 controls. The blood and lymph basins of conjunctive, eyelids and eyeglobe were visualized by Gerot blue mass administration. Histological topography relationships were examined in conjunctive lymph and blood basins and surrounding tissues applying light microscopy in slices painted by hematoxylin-eozine, chromatrope and basic brown.

At 8 Hz, 100 and 140 dB (5 day exposure), the narrowing of all parts of conjunctive blood basin was found. The blood capillary lumen decrease was accompanied by cytoplasm and endotheliocyte nuclei enlargement. Capillaries, pre-capillaries and arterioli are gyrose. In venous vessels, blood component agglomerations were found.

Morphological functional changes of conjunctive vessels of blood and lymph basin were accompanied by changes in cellular and non-cellular components of the connective tissue. In blood and lymph vessels, the number of adventitious and free fatty cells (labrocytes) is increased. These cells are changed including large labrocytes found in the connective tissue. The cytoplasmic membrane of fatty cells is ruptured and single granules have occurred in the cellular surface and interstitial substance. Collagenic filaments of the

conjunctive connective tissue are enlarged insignificantly. Some fibroblast nuclei are enlightened and enlarged.

After 10 day infrasound exposure, conjunctive capillaries are twisted. The large vessel diameters are decreased and endothelium cell nuclei are enlightened and moved inside the vessel, which lumen is split-like. Vascular reactions of lymph vessels are the same.

The conjunctive connective tissue is also changed. Fatty cells are re-distributed and positioned in vascular areas of the conjunctive. Labrocytes are changed in forms and activity. Increased degranulation is noted. Some fatty cells are completely disintegrated.

Labrocyte granule destruction results to the heparin release, which apparently prevents agglutination within 10 days of the exposure. This concludes to adaptation of fatty cell apparatus.

In case of 15 day exposure, the tone of blood and lymph vessels is changed in conjunctive and stagnation has occurred.

In case of 25 day exposure, the failure of tissue homeostasis is aggravated. The capillary penetration is increased, which manifests via tissue enlargement and leukocyte infiltration. Significant agglutination was noted in large vessels.

Thus, the blood basin changes are progressed in case of the increased exposure time; these changes include agglutination, peri-vascular infiltration and twisted capillaries and vessels. Lymph vessel changes are accompanied by lymph aggregation and changed configuration of lymphatic vessels. The change of vascular tone in blood and lymph basins causes the trophicity disturbances in cellular and non-cellular components of conjunctive connective tissue.

The infrasound exposure has exhausted adaptive abilities of fatty cells, which causes the capillary penetration increase and blood agglutination.

2001 paper was devoted to infrasound and noise effects in vision organ for 214 workers of armored concrete factory. 2 groups were separated. 160 examined persons (moulders) were exposed to industrial infrasound of 96-100 dB and 8 and 16 Hz and noise of 91-93 dB A. The control group (54 persons) was not affected by the infrasound. Both groups were composed of males (20 to 58 year ages) with employment duration of 1 to 30 years. The vision power and color perception were examined; perimetrium, external examination, biomicroscopy, ophthalmoscopy and tonometry were tried.

Experimental study was also tried in 30 rabbits exposed to 100 dB within 30 days (3 h/day) in the infrasound chamber. The rabbit applied infrasound frequencies were 8 Hz (series I) and 16 Hz (series II). Series III rabbits (control) were not exposed. Clinical examinations of rabbit vision organ (external examination, biomicroscopy, ophthalmoscopy) and morphological examinations (light microscopy of enucleated eyeglobe) were tried at days 3, 7, 15, 30, 60 and 90 after exposure.

The examined workers had 11 % increase of the morbidity rate (transient loss of the workability). Vision function complains were not noted. Vision power and color perception were not disturbed. Vision fields and ophthalmotonus were normal. Tear organs were normal. Transparent media were not changed. The iridescent envelope was unchanged and light reaction was normal. The eyeground was as follows: vision nerve disk of clear borders and pale pink color. The macular zone is normal. However, conjunctive eyelid and eyeglobe vascular system changes were found (Table 3.30) as well as the eyeground vessels if compared to the control group. After 2 years of the employment, moulders have not significant vascular changes in conjunctive. Within followed 8 years of the employment, the increased number of persons with enlarged (up to 82.1 %), narrowed (up to 17.9 %) and twisted (up to 80 %) vessels was noted; besides, single non-vascularized conjunctive sites were noted in some persons (5.9 %). In case of 11-20 year employment, conjunctive and vessels were narrowed (91.7 %), more twisted (100 %); the number of non-vascularized conjunctive eyelid and sclera site persons was increased (13.9 %). In > 20 year employed moulders, vessels were strongly narrowed and twisted and non-vascularized conjunctive sites were noted in 47.4 %.

Table 3.30 - Vascular changes in eyelid and eyeglobe conjunctive in armored concrete factory workers

Group	No.	Vascular change character								Non-vascularized sites	
		unchanged		enlarged		narrowed		twisted			
		Abs.	%	Abs.	%	Abs.	%	Abs.	%	Abs.	%
Control group	54	54	100	0	0	0	0	0	0	0	0
Groups of work period, years											
1—2	21	21	100	0	0	0	0	0	0	0	0
3-10	84	0	0	69	82.1	15	17.9	67	80	5	5.9
11—20	36	0	0	3	8.3	33	91.7	36	100	5	13.9
21—30	19	0	0	0	0	19	100	19	100	9	47.4

The conjunctive vessel examinations have revealed their significant changes, which were dependent upon the employment time. Authors suppose that conjunctive vessel changes reflect general vascular pathology.

Retinal vessels were found to be changed. After 3-10 years of work, each moulder had changed retinal vessels: 13 % (narrowed) and 75 % (twisted); arteries were narrowed in 91.7 % and twisted in 90.4 % of workers (Table 3.31). After 11-20 years of work, all workers were found to have more expressed narrowing and twisting of arteries and veins of the retina. After > 20 years of work, the significant narrowing and twisting of arteries and veins were found. All workers of any employment time had more expressed arterial than venous changes.

Table 3.31 - Retinal vascular changes in armored concrete factory workers

Group	No.	Arteries are:							
		unchanged		enlarged		narrowed		twisted	
		Abs.	%	Abs.	%	Abs.	%	Abs.	%
Control group	54	54	100	0	0	0	0	0	0
Groups of work period, years									
1—2	21	21	100	0	0	0	0	0	0
3-10	84	0	0	0	0	77	91,7	76	90,4
11—20	36	0	–	0	0	36	100	36	100
21—30	19	0	0	0	0	19	100	19	100
Group	No.	Veins are:							
		unchanged		enlarged		narrowed		twisted	
		Abs.	%	Abs.	%	Abs.	%	Abs.	%
Control group	54	54	100	0	0	0	0	0	0
Groups of work period, years									
1—2	21	21	100	0	0	0	0	0	0
3-10	84	0	0	73	87.0	11	13	63	75
11—20	36	0	0	4	11.1	32	88.9	35	97.2
21—30	19	0	0	0	0	19	100	19	100

To determine morphological changes of the vision organ, two experimental series were analyzed. At day 3 of the exposure, clinical changes were not observed. However, morphological examinations have demonstrated, that edema of upper and middle areas of eyelid derma is present (series I) as well as the heterogeneous blood filling of vessels with extra-vascular erythrocytes. Under the conjunctive epithelium, the focal lymphoid cellular infiltration was noted. In series II, the eyelid skin edema was more expressed together with capillary stasis and extra-capillary erythrocytes. Fresh fine focal hemorrhages were observed under the corneous layer of the eyelid. The focal lymphoid cellular infiltration was found under the conjunctive eyelid, which was more expressed if compared to series I. Collagen filaments of the sclera were separated due to edema.

Sclera vessels were filled heterogeneously with stasis and extra-vascular intra-conjunctive hemorrhages. Iris edges have contained focal pigment depositions disseminated to the frontal ascus of the lens. Moderate edema is present in the vision nerve stretch. Besides, series II animals had peri-neural hemorrhages in the vision nerve.

At day 7 of the exposure, conjunctive vessels were expanded and eyeground arteries were narrowed and twisted. In both series, the expressed eyelid skin edema was found together with collagen decompensation. Most expressed vascular reaction (stasis, edema, peri-capillary hemorrhages) was observed in the eyelid conjunctive. Sclera capillaries were blood overfilled and extra-vascular hemorrhages were present. The lens epithelium was saved but epitheliocytes nave contained focal vacuoles. In series I, the heterogeneous edema was observed in all retinal layers with higher expression in the neuron level. In series II, retinal changes were more expressed if compared to series I.

At day 15, conjunctive vessels are twisted; very narrowed and non-vascularized areas are present in eyeglobe conjunctive. Morphological examinations in both series have revealed expressed vascular reaction (edema, paresis state of capillaries, and extra-vascular erythrocytes). Vascular disorders were noted in conjunctive (edema, erythrocyte stasis with extra-vascular hemorrhages).

The focal and disseminated disorganization of sclera collagen was observed. The iris was hyper-pigmented; its vessels were narrowed (angiospasm). The lens epithelium thickness was non-uniform. The photosensorial retinal layer has contained edema, initiated sub-atrophy and focal reactive hyperplasia. Series II animals have been found to have expressed sub-atrophy and atrophy changes in photosensorial retinal neurons.

At day 30, the narrowing and twisted conjunctive vessels were clinically detected; eyeground arteries and veins were significantly narrowed and twisted (more expressed in series II). In series I, parakeratosis and hyperkeratosis of the eyelid conjunctive were found as well as the homogenization and disorganization of eyelid skin collagen. Expressed vascular disturbances were present in conjunctive (erythrocyte stasis and edema). Disseminated lymphoid cellular infiltration was also noted. Dystrophic changes and eyelid desquamation were noted in conjunctive epithelium. Eyelid changes are more expressed in series II. In series I, collagen filaments of sclera were separated due to the edema; some filaments are dystrophic and necrobiotic. Sclera arteries and veins are enlarged, blood overfilled and extra-vascular focal and diffuse hemorrhages are present with conjunctive involvement. The iris was noted to have expressed hyper-pigmentation with melanin release. The retina was noted to have layer disorganization most expressed in photosensorial layer, where dystrophic changes and partial death of neurosensorial cells were noted. In series II, more expressed destruction was found in all eye structures.

After the infrasound exposure termination, the gradual recovery of changes was observed. At day 60 (day 30 after the exposure termination) the conjunctive and retina vessels were less twisted and narrowed. The morphological recovery was slower: at day 60, fine focal lymphoid cellular infiltration and moderate regeneration were noted in eyelid conjunctive epithelium. The iris capillaries at paresis state are anemic. In series II, morphological signs of predominant retinal damage have persisted (layer disintegration, dystrophic changes of neurosensorial cells in photosensorial and exterior nuclear layers).

At day 90, vision organ changes were not clinically revealed.

Thus, infrasound and low frequency noise affect vascular system of conjunctive and retina of exposed workers. The expressiveness of these changes is proportional to the employment period.

The experimental infrasound exposure of 100 dB, 8 and 16 Hz was found to induce significant changes in almost all eye structures. Their expressiveness is proportional to the exposure time.

Most significant morphological changes include edema, dystrophy and vascular disturbances.

Infrasound intensity of 100 dB (16 Hz) has induced more expressed changes in all tissues of the vision organs if compared to 8 Hz infrasound. These changes have been recovered for longer period of time.

3.10 Genetic apparatus (bone marrow cells) affected by LFAO

Literature data (Svidovy V.I., Kitaeva L.V., 1998) certify to the fact that LFAO effect mechanism is significantly determined by the initial damage of structure and function of cells.

The decrease of succinate dehydrogenase activity in cerebral tissues and cardiac muscle of experimental animals exposed to the long term infrasound indicates to deep structural changes of mitochondrial membranes, which are accompanied by the antioxidant system exhaustion and result to the structure and function disturbances of the membrane ferments.

Electronic microscopic examinations of internal organs have demonstrated that the exposure at 2 to 16 Hz 90 to 120 dB induces mitochondria changes. The enlargement, diminishing and disorganization of crests, vacuole production and destruction were present in cellular mitochondrias. It certifies to the fact that most sensitive parts (mitochondrias) are the first reaction sites.

It is known that noise is unable to destroy chemical covalence links in the biological membranes; however, it is able to affect to the weak electrostatic covalence interactions, which would change the cell activities and its biochemical homeostasis. The function of endocrine glands (thyroid, adrenals) can be changed and these changes can affect inheritable structures.

The noted authors have tried to assess infrasound effects in genetic apparatus.

The infrasound cluster producing effect investigation was elaborated via structural damage counting in the bone marrow metaphases of non-linear white male rats in accordance with General Genetics Institute recommendations. Five animal groups (10 animals per group) and control group were exposed at 2, 4, 8 and 16 Hz and 90 and 110 dB within 1 month (3 h/day). Fifth group was exposed to 100 dB within 2 months. At the end of the experiment, animals were sacrificed at hour 24 after the exposure termination. 100 metaphases were analyzed for each animal. The following indices were considered: chromosome aberration cell percentage, number of aneuploid and polyploid cells, number of metaphases with chromatin destruction. Mitosis index was evaluated. Statistical analysis was done applying Student criterion.

The number of aberrant and aneuploid cells was statistically homogeneous inside variants, which provides the summation ability (see Table 3.32). The chromosomal disturbance cell incidence was 0.6 to 1.3 % (control group) and 0.2 to 1.2 % in any experiment variant, which is the confident difference.

At 2 Hz and 90 and 110 dB (see Table 3.32), the increase of metaphase with structural chromosomal damages was 2 and 3 folds, respectively, however these differences are not statistically confident. The chromosome aberration type analysis has not revealed differences versus control; basically, the infrasound exposure has increased the number of chromatid damages (chromatid divisions).

The analysis of aneuploid cell incidence has not revealed significant differences of experiment vs. Control, which certifies to the absence of infrasound effect (at tested frequencies and intensities) in cellular division mechanisms in the bone marrow of experimental animals.

The mitosis activity of rat bone marrow cells was examined via the assessment of dividing cells per 1,000 cells examined. Average mitosis index is provided by Table 3.32. The confident mitosis decrease ($p<0.01$) was observed at 4 Hz, 90 and 110 dB, and also at 2 Hz and 110 dB ($p<0.05$). Besides, the leveling of this index is very high, which complicates the analysis of results.

To be assured in the absence of the infrasound mutagenic effect, the experiment was tried in animal group 5. The frequency applied was the frequency inducing most expressed biochemical and morphological changes (8 Hz and 100 dB). The exposure time was extended to 2 months. Indices were the same. The chromosomal damage cell incidence was 0.8 %, which corresponds to the literature data.

Table 3.32 – Aberrant metaphase incidence rate in bone marrow cells of non-linear rats exposed to infrasound within 30 days (n=5)

Experiment conditions	Analyzed metaphase number	Aberrant cell number		Aneuploid cell number		Mitosis index (%±m)
		Abs.	%±m	Abs.	%±m	
Control	500	3	0.6±0.35	67	13.4±1.52	42.8±3.23
2 Hz 90 dB	500	6	1.2±0.49	61	12.4±1.47	49.2±3.3
2 Hz 110 dB	500	10	2.0±0.63	49	9.8±1.33	35.4±1.4*
Control	300	4	1.3±0.65	58	19.3±2.3	26.3±2.05
4 Hz 90 dB	500	6	1.2±0.49	66	13.2±1.54	12.8±0.7**
4 Hz 110 dB	500	4	0.8±0.39	62	12.9±1.47	13.8±1.16**
Control	500	3	0.6±0.35	77	15.4±1.62	30.6±0.91
8 Hz 90 dB	500	1	0.2±0.19	86	17.2±1.68	35.4±6.45
8 Hz 110 dB	500	2	0.4±0.28	65	13.0±1.5	27.6±1.82
Control	300	3	1.0±0.57	56	18.7±2.25	21.3±2.05
16 Hz 90 dB	500	1	0.2±0.59	84	16.8±1.67	32.6±3.65
16 Hz 110 dB	500	4	0.8±0.39	101	20.2±1.8	24.6±1.19

Note: * confident difference versus control ($p<0.05$), ** ($p<0.01$).

The analysis of 2 month exposure data (3 h/day) has not revealed the confident differences versus control ($p<0.05$). Table 3.33 indicates that the infrasound exposure has decreased the mitosis index ($p<0.01$), which is probably related to the delayed mitosis cycle.

Table 3.33 - Cytogenetic infrasound effects (8 Hz and 100 dB) in bone marrow of non-linear male rats after 2 month exposure

Experiment conditions	Analyzed metaphase number	Number of cells with structural changes		Aneuploid cell number		Mitosis index per 100 nuclei (%±m)
		Abs.	%±m	Abs.	%±m	
Control	400	3	0.8±0.43	73	18.2±1.9	33.2±1.23
Infrasound	400	5	1.2±0.56	70	17.5±1.9	21.5±1.62*

Note: * confident difference versus control ($p<0.01$).

Thus, the cluster producing effect of the infrasound is absent for examined frequencies and intensities.

It was concluded that infrasound exposure at 2 to 16 Hz and 90 to 110 dB (1 - 2 month duration) has induced the increased number of chromatid damages (chromatid divisions) and mitosis rate delay in bone marrow cells of experimental animals.

According to N.N. Pluzhnikov et al (2001), the LFAO exposure results to very significant changes of nucleoproteid metabolism. Such conclusion (together with mitochondrial membrane structure disturbances) was the reason to test LFAO exposure effects in genetic cellular apparatus applying chromosomal test. Table 3.34 concludes to the following: LFAO is specific to expressed mutagenic effect, which is manifested within one day after the exposure in the aberrant cell count increase to 11%, which certifies to possible premature cell aging resulted from "mistake" accumulation in DNA structure due to the genome destabilization and increased neoblast production. It should be also noted that LFAO effects were similar for SPLs of 120 and 150 dB. Thus, this physical factor is able to kill cells not only via interphase but also via post-mitosis mechanisms.

Table 3.34 - Single LFAO exposure effect in chromosomal aberration rate in rat bone marrow cells (24 hours after exposure) ($M \pm m$, $n = 6$) (Pluzhnikov N.N. et al, 2001)

Index	Before exposure, control	After exposure to SPL_{peak}, dB	
		120	150
Analyzed cell number	600	600	600
Aberrant cell number, abs. (%)	6 (1.0 ± 0.4)	68 (11.3 ± 1.31)	63 (10.5 ± 1.2)
Aberration number, abs. (%)	6 (1.0 ± 0.4)	80 (13.3 ± 1.4)	75 (12.5 ± 1.1)
Aberration types:			
Single fragments	2	14	9
Pair fragments	4	46	42
Dicentrics	0	10	12

3.11 Bioenergetics and regulation processes (biochemical aspects) under LFAO exposure

S.V. Alexeev et al, (1983) in acute and chronic experiments have examined LFAO effects if phosphotide content of integral blood, liver and brain of animals (rats).

Matured white rats were exposed to single infrasound (3 h, 4 Hz, 90 dB) and multiple infrasound (40 days, 4 Hz, 140 dB; 5 and 15 days, 8 Hz, 120 dB; each daily episode time was 3 h).

Integral blood samples (3 mL) and brain and liver samples (1 g) were stabilized by chloroform-methanol mixture (2:1). Lipids were examined applying technique developed by Folch et al

Phosphotides were fractionated applying thin slice chromatography according to L.N. Velichko et al. Five fractions were examined: lyzophosphatide cholines, sphingomyelins, phosphotidil cholines, phosphotidil serines, phosphotidil colamines.

Integral blood phosphotides in LFAO exposed and control rats were found to be represented by phosphotidil cholines and phosphotidil colamines; other fraction contents are below 10%. At 4 – 8 Hz, 90 to 140 dB (3 h, 5, 15 and 40 days) the phosphotide fraction contents in the integral blood were similar to control ones.

The thin slice chromatography of hepatic phosphotides has resulted to seven fractions. Contents of phosphotidil cholines, phosphotidil colamines and sphingomyelins were higher; the seventh fraction was composed of phosphotide acids and polyglycerophosphatums; other fractions were below 10%.

LFAO exposure has not significantly changed phosphotide fraction contents in liver if compared to control ones.

Phosphotide fraction contents in rat brain are provided by the Table 3.35. Phosphotides of the rat brain are separated into 6 fractions including phosphotidil cholines, phosphotidil colamines and phosphotidil serines; the sixth fraction is composed of phosphotide acids and polyglycerophosphatums.

LFAO exposure has not significantly changed phosphotide fraction contents in rat brain in case of acute tests (3 h) and exposure times of 5 and 15 days. In case of 40 day exposure at 4 Hz, 140 dB, the cerebral phosphotides has been changed. Insignificant increase of phosphotidil cholines was noted (from 39.6±1.4 % in control to 44.6±1.12 % ($p<0.05$)) as well as the phosphotidil inozitoles (from 6.4±0.8 % in control to 4.1±0.4 % ($p<0.05$)) and phosphotide acids and polyglycerophosphatums (from 7.3±0.5 % in control to 4.2±0.6 % ($p<0.05$)). These data indicate to the delayed metabolism of acidic phosphotides and increased metabolism of phosphotidil cholines in case of long (40 days) LFAO exposure.

40 day exposure at 4 Hz, 140 dB has, apparently, induced the excitation focus in the brain, which irradiates to other cerebral

compartments. Apparently, the delayed phosphotidil inozitoles metabolism has changed the penetration of pre- and post-synapse membranes of synapses, which is accompanied by the phosphorylation disturbance in receptor, catalysis membrane, and cytoplasmic albumins.

Table 3.35 - Relative content of phosphotide fractions in the rat brain in case of LFAO exposure (M ± m)

Test conditions	Phosphotide fractions:					
	sphingo-myelins	phosphotidil cholines	phosphotidil inozitoles	phosphotidil serines	phosphotidil colamines	phosphotide acids + polyglycero-phosphatums
control n = 8	6.4±0.6	39.6±1.4	6.4±0.8	10.5±0.9	28.4±1.2	7.3±0.5
3 h - 8 Hz, 120 dB n = 7	6.2±0.8 p>0.05	41.0±1.8 p>0.05	6.2±0.7 p>0.05	11.4±0.8 p >0.05	29.3±1.4 p>0.05	6.8±0.8 p>0.05
5 days - 8 Hz, 120 dB n = 9	5.9±0.9 p>0.05	50.0±1.9 p>0.05	7.0±0.8 p>0.05	9.8±0.7 p>0.05	30.1±1.6 p>0.05	7.0±0.7 p>0.05
15 days - 8 Hz, 120 dB n = 8	7.1±0.8 p>0.05	38.1±1.2 p>0.05	6.0±0.6 p>0.05	10.4±0.6 p>0.05	28.1±1.8 p>0.05	8.0±0.9 p>0.05
40 days - 4 Hz, 140 dB n = 9	6.9±0.9 p>0.05	44.6±1.1 p<0.05	4.1±0.4 p<0.05	9.9±0.7 p>0.05	29.2±1.5 p>0.05	4.2±0.6 p<0.05

Increased phosphotide choline in rat brain certifies to increased metabolism of different parts of phosphotide molecules in membrane including the synthesis acceleration or disintegration delay.

Found phosphotide changes induced by LFAO exposure in the rat brain have probably resulted to changed neuron membrane functions, which can cause functional disorders in cardiovascular and respiratory systems.

It was concluded that low frequency acoustic oscillations at 4 Hz, 90 and 140 dB (3 h and 40 days) and at 8 Hz, 120 dB (5 and 15 days) have not changed phosphotide fraction contents in the integral blood and liver of experimental animals.

The long term (40 days) exposure at 4 Hz, 140 dB has induced the increase of phosphotide cholines and decrease of phosphotide inozitoles as well as the decrease of phosphotide acids + polyglycerophosphatums in the rat brain.

The obtained data indicate to the changed phosphotide metabolism in rat brain including the increase of neutral phosphotide metabolism and decrease of acidic phosphotide metabolism in case of LFAO exposure at 4 Hz, 140 dB.

V.I. Svidovy and A.G. Shleykin (1987) have obtained data indicating to the fact that infrasound is able to change the native structure of biological membranes and activity of membrane ferments including catalase and choline esterase of erythrocytes.

The modification of integral ferments in membrane (acetyl choline esterase and catalase) is the sign of deep structural disorders induced by the infrasound.

The catalase inactivation results to the decrease of the anti-peroxide activity of the cell and integral ability of the anti-oxidative system.

The stabilization of the anti-oxidative homeostasis is impacted by co-ferment recovery systems (tricarbonic acid cycle) localized in mitochondrias. The state of mitochondria ferments in case of the infrasound exposure is the subject of specific interest.

The purpose of study was the succinate dehydrogenase (SDH) effect examination in case of chronic infrasound exposure at 4, 8 and 16 Hz and 100 and 130 dB (5, 10, 15, 25 and 40 days, 3 h/day).

White male rats (125±5.0 g initial body weights) were examined. 10 series (10 animals/series including 3 animals in control)were tried. Ferment activity was examined in homogenate of large cerebral hemispheres and cardiac muscle applying spectrophotometry. Pair values were compared in the dependent totalities to determine the variation coefficient.

It was established that 4 Hz exposure has decreased cerebral SDH activity at day 5 as follows: 79.5% (100 dB) and 82% (130 dB) ($P>0.05$) (see Table 3.36). Within the increase of the exposure time, the ferment activity has gradually recovered. At day 40, the SDH activity was depressed again.

In the heart muscle, the ferment activity depression was noted at days 5 and 10 ($P<0.05$); at days 15 and 25, the activity was elevated.

At 8 Hz and 100 dB, SDH activity in the myocardium has increased within the exposure time course. High activity has persisted at days 15 and 25; in case of 40 day exposure, the SDH activity was decreased to 69.3 and 73.4%, respectively. In cerebral tissues, the decrease SDH activity trend was noted in case of the increased exposure time. At 16 Hz, 100 and 130 dB (days 5, 10 and 15), SDH myocardial activity was unchanged. At day 25, it has increased; 40 day exposure has not significantly affected SDH activity. In cerebral tissues, the SDH activity was significantly elevated at days 5, 10 and 15 and was similar to the control level at later terms.

Thus, the SDH activity effect of the infrasound exposure of examined frequencies and intensities is determined by the frequency. The myocardial ferment activity is decreased for low exposure periods at 4 Hz; in case of the increased exposure period, this activity is close to the control level. Alternatively, 5 day exposure has induced SDH activity increase in cerebral tissues, which activity was recovered at day 10.

Table 3.36 - SDH activity in brain and heart of experimental animals (rats) exposed to the infrasound (mmol/min)

Exposure parameters	Observation number	Brain				
		Exposure time, days				
		5	10	15	25	40
Control	30	0.39±0.04	0.65±0.08	0.48±0.02	0.62±0.08	0.38±0.05
4 Hz, 100 dB	10	0.31+0.04	0.64+0.05	0.69+0.05	0.66+0.02	0.36+0.03
	p	>0.05	>0.05	<0.01	>0.05	>0.05
4 Hz, 130 dB	10	0.32+0.03	0.79+0.05	0.66+0.02	0.63+0.18	0.34+0.05
	p	>0.05	<0.05	<0.01	>0.05	>0.05
8 Hz, 100 dB	10	0.59-0.05	0.32+0.15	0.60+0.05	0.54+0.07	0.34+0.04
	p	<0.05	<0.05	<0.U5	>0.05	>0.05
8 Hz, 130 dB	10	0.52+0.07	0.31+0.04	0.39+0.05	0.38+0.15	0.36+0.05
	p	<0.05	<0.05	<0.05	<0.05	>0.05
16 Hz, 100 dB	10	0.43+0.02	0.59+0.07	0.41+0.03	0.18+0.04	0.34+0.06
	p	>0.05	>0.05	>0.05	<0.05	>0.05
16 Hz, 130 dB	10	0.42+0.03	0.39+0.05	0.30+0.03	0.16+0.01	0.33+0.07
	p	>0.05	<0.05	<0.05	<0.05	>0.05
Exposure parameters	Observation number	Heart				
		Exposure time, days				
		5	10	15	25	40
Control	30	2.02±0.2	2.09±0.15	1.79±0.05	1.65±0.19	1.5±0.2
4 Hz, 100 dB	10	0.63+0.06	0.66+0.13	2.02+0.1	1.86+0.2	1.22+0.05
	p	<0.05	<0.05	<0.05	<0.05	<0.05
4 Hz, 130 dB	10	0.83+0.03	2.05+0.14	2.16+0.06	1.84+0.03	1.52+0.06
	p	<0.05	>0.05	<0.05	<0.05	>0.05
8 Hz, 100 dB	10	1.84+0.18	1.5+0.16	1.65+0.19	1.92+0.18	2.01+0.13
	p	>0.05	<0.05	<0.05	<0.05	<0.05
8 Hz, 130 dB	10	1.74+0.2	2.07+0.05	2.27+0.2	2.01+0.04	1.84+0.19
	p	<0.05	>0.05	<0.05	<0.05	<0.05
16 Hz, 100 dB	10	1.18+0.04	2.04+0.06	1.97+0.17	1.92+0.24	1.06+0.08
	p	<0.05	>0.05	<0.05	<0.05	<0.05
16 Hz, 130 dB	10	0.95+0.10	1.77+0.08	1.78+0.15	2.08+0.15	0.85+0.14
	p	<0.05	<0.05	>0.05	<0.05	<0.05

The persistent increase of SDH activity was found in the cardiac muscle in case of 8 Hz exposure of any examined intensities, whereas the slight decrease was found in the brain. Myocardial ferments has reacted at day 25 only (16 Hz); the activity was decreased ad day 40 (p<0.05). CDH cerebral activity was elevated at day to 25; thereafter, it was decreased to control level, which can be interpreted as the adaptation. The incongruity of adaptation and disadaptation in different organs indicates to the possible direct infrasound effect in plasmatic and mitochondrial membranes of different cells and tissues. The membrane response to the infrasound exposure is specific to two phases: activation and depression of the ferment activity. SDH activation can be attributed to adaptation directed to repair cellular structures via accelerated

production of recovered co-ferments of tricarbonic acid cycle promoting the anti-oxidative system (AOS) abilities.

The noted cerebral and cardiac SDH activity decrease for increased exposure periods has indicated to deeper changes of mitochondria membranes, which are accompanied by AOS exhaustion and disturbance of membrane ferments. Similar data were obtained for "white" noise effects in AOS, which indicates to common regularities of biological membrane reactions to sound and infrasound exposure and to the AOS importance for adaptation of different tissues, organs and whole organism.

The SDH activity variation coefficient was 40 % (brain) and 26 % (heart), which gives the opportunity to recommend this ferment assessment to evaluate physical factor effects, taking into account variation coefficients of flexible indices.

It was concluded that SDH activity was basically affected by the exposure frequency. Besides, the direct infrasound effect in membranes is possible, because the membrane response consists of two phases: adaptation and depression of membrane ferments.

According to modern understandings, the long term infrasound exposure of 90–110 dB is a strong stress factor and is able to induce the adaptation failure. V.I. Svidovy et al (19??) have previously demonstrated the frequency and exposure time ratios of the effect in separate body systems and biochemical indices, which were correlated to infrasound adaptation and disadaptation development.

V.A. Dadali, V.I. Svidovy, V.G. Makarov et al, (1992) have examined infrasound effects in AOS state and some other biochemical indices of experimental animals as well as the possibility to increase the organism resistance applying compounds containing imidazole nucleus. Such compounds were Etimizole preparation and original T-5 compound derived from 2-phenyl-benzimidazole.

Experiment was tried in white non-bred male rats. 6 animal groups were involved (10 animals/group). Group 1 was the control. Group 2 was exposed at 8 Hz and 100 dB (2 months, 3 h/day). Groups 3 and 4 were also exposed to the same infrasound but were administered by Etimizole and T-5 (2 μmol/kg daily with drinking water with 1 week interval). Daily dosage was 10 times lower than usual therapeutic dosages. Group 5 and 6 were administered by Etimizole and T-5 only. At days 7, 30 and 60 from the beginning of the experiment, activities of superoxide dismutase, catalase, glutathione reductase (GR), glucose-6-phosphate dehydrogenase (G-6-PDG) and the intensity of peroxide oxidation of lipids (POL) via malonic dialdehyde (MDH) amount, hepatocuprein (HC) activity, alanine and asparthate amine transferase activities were assessed in the blood plasma applying routine spectrophotometry. Animal organs were examined at the end of the experiment applying light microscopy.

Table 3.37 and 3.38 demonstrate that infrasound of examined frequency and intensity has affected AOS components (excluding superoxide dismutase) and POL intensity. At day 30, MDH erythrocyte concentration was elevated for 26%; GR and HC activities were elevated for 29 and 41 %, resp. Both compounds (Etimizole and T-5) have normalized POL intensity with confident MDH decrease to the normal level; Etimizole and T-5 have not affected the ferment activity in erythrocyte AOS, whereas T-5 has increased HC activity in the blood plasma. At day 60, HC and GR activities were elevated together the catalase activity increase. At that period, Etimizole has significantly (for 30-40 %) decreased POL intensity and HC oxidative activity if compared to the control and to group 2; T-5 has elevated catalase activity in erythrocytes (25 %), GR (51 %), G-6-PDG (27 %) with unchanged POL intensity, if compared to the control.

Table 3.37 - Infrasound effects (8 Hz, 100 dB within 2 months) in erythrocyte AOS (M±m)

Test conditions	Catalase, cond. units per 1 kg of albumin			MDH, μmol/L			GR, cond. units per 1 kg of albumin		
	Experiment time								
	7	30	60	7	30	60	7	30	60
Control	259.5±31.4	243.0±22.4	242.4±6.2	6.9±0.5	6.6±0.5	6.7±0.6	7.5±0.6	8.0±0.64	8.0±0.64
Infrasound	225.0±31.0	274.0±15.0	300.0±13.0	7.0±0.5	8.3±0.3	7.0±0.3	8.0±0.6	10.3±0.4	10.0±0.5
Etimizole and Infrasound	229.0±26.0	219.5±46.2	228.1±8.6	2.9±0.4	5.9±0.6	4.4±0.7	8.6±0.5	8.2±0.5	9.0±0.7
Etimizole	248.6±26.2	295.2±39.5	244.0±17.0	5.0±0.5	6.7±0.7	4.0±1.0	9.3±0.6	8.9±0.5	9.2±0.5
T-5 and Infrasound	205.0±10.0	253.0±25.0	302.0±17.1	8.4±0.5	6.9±0.5	6.5±0.4	10.0±1.7	10.3±1.1	12.0±1.3
T-5	230.0±22.0	268.1±16.2	279.5±21.4	8.7±0.2	7.5±0.7	7.0±0.2	9.4±1.2	9.7±1.3	8.7±0.4

Table 3.38 - Infrasound effects (8 Hz, 100 dB; 2 months) in blood plasma AOS (M±m)

Test conditions	Hepatocuprein, μmol/L			Alanine amine transferase, cond. units per 1 kg of albumin			Asparthate amine transferase, cond. units per 1 kg of albumin		
	Experiment time, days								
	7	30	60	7	30	60	7	30	60
Control	3.3±0.4	3.8±0.3	4.1±0.6	5.8±0.2	6.9±0.4	7.3±0.5	10.4±0.6	10.5±0.5	10.7±0.4
Infrasound	4.2±0.5	5.4±0.4	6.0±0.6	8.8±1.1	9.2±0.6	8.2±0.4	8.5±0.4	12.3±1.2	10.7±0.7
Etimizole and Infrasound	3.5±0.4	4.0±0.3	2.9±0.3	7.4±0.6	8.2±0.7	8.8±0.6	7.8±0.5	11.7±0.6	11.2±0.4
Etimizole	4.7±0.5	4.4±0.2	2.6±0.6	8.5±0.4	9.3±1.3	6.8±0.3	8.1±0.4	10.2±0.6	12.0±0.6
T-5 and Infrasound	3.1±0.4	5.3±0.4	4.6±0.5	7.8±1.0	8.4±0.8	6.7±0.7	11.0±0.9	11.1±0.5	10.7±0.5
T-5	3.4±0.2	4.4±0.3	4.5±0.3	7.0±0.2	7.1±0.5	7.3±0.7	10.0±0.9	8.9±0.5	11.2±0.5

Apparently, the increased activity of alanine amine transferase in the blood plasma at days 7 and 30 certifies to the pathological effect in hepatocytes, which is confirmed by histology tests. Both compounds have normalized blood plasma transaminase activities.

The infrasound exposure has induced biochemical shifts related to the increased free radical oxidation intensity. It has caused POL intensity increase and AOS ferment activity elevations of compensatory type. Apparently, Etimizole directly affects AOS, which is indirectly confirmed by the dynamics of blood plasma lipid ozonization. The agent has decreased POL intensity and HC oxidative activity. The direct T-5 anti-oxidative effect was not found, so POL intensity decrease is apparently related to the induction of AOS ferment synthesis. The activity increase of G-6-PDG and GR is essentially important for erythrocyte AOS function. Obviously, the simultaneous application of both agents is more effective, because the endogenic AOS stimulation will be present together with direct anti-oxidative effect.

The internal organ histology (lungs, liver, kidneys and adrenals) has confirmed biochemical changes. In case of the infrasound exposure, all these organs would develop destructive and atrophic changes of focal character without rough disorders; in lungs, liver and kidneys the moderate plethora was observed as well as the focal proliferation of stroma elements. The application of imidazole derivates has significantly decreased unfavorable infrasound effects. Only insignificant peri-bronchial infiltrates were noted in lungs. Dystrophic changes in liver, heart, kidneys, and adrenals were minimized.

Thus, the long term infrasound exposure at 8 Hz and 100 dB has induced significant biochemical and morphological changes in blood and tissues; imidazole derivates (Etimizole and T-5) provide expressed protection even in insignificant concentrations, because of the influence in anti-oxidative status. These agents are perspective for adaptation stimulation.

3.12 Infrasound effects in immune reactivity and peculiarities of forming of immediate hypersensitivity in case of the infrasound exposure

It is known that organism sensibilization and immediate hypersensitivity development are process specific for the allergen. Anaphylactic reaction would only develop, is the sensibilization allergen is applied for solving administration. According to these conditions, the fatal reaction will develop in 80-100% of guinea pigs. The decrease of shock reaction down to the complete diminishing can be only elaborated applying the initially applied allergen.

Recently, papers have been published to indicate to the possibility of the effect modification if non-ionizing physical factors are applied. G.I. Vinogradov et al (1974, 1975) have established that continuous microwaves of 50 $\mu W/cm^2$ promote autosensibilization. Authors have got the anaphylactic shock inhibition in sensibilized animals exposed before the solving antigen administration. The constant magnetic field was found to induce the significant difference of anaphylactic activity of "magnetized" and "non-magnetized" antigen. The initial administration of "magnetized" alien albumin in intact animals has been found to show the anaphylactic reaction, whereas the sensibilized animals the decrease of the reaction severity was observed in case of "magnetized" antigen provocation.

First immune studies of the infrasound have demonstrated its ability to amplify allergic sensitivity (Shutenko O.I. et al, 1979). It was established that infrasound exposure at 8 Hz and 90 to 135 dB has induced 3-5 times increase of Shelly reaction and 2 times increase of autoplaque number in rats.

Our earlier experiments have demonstrated the infrasound effect realization via humoral immunity (Grigoriev Yu.G., Stepanov V.S., Batanov G.V., 1981). The above mentioned considerations have indicated to possible allergic status modification applying physical factors of different origin.

To check this assumption, the Institute of Biophysics has tried experiments in 230 guinea pigs applying classical model of anaphylactic shock (original study). Animals were exposed at 10 Hz and 155-160 dB within 10 min before the i.v. administration of alien albumin (integral horse serum). The exposure was tried at different terms after the i.p. sensibilization with the same antigen. Non-irradiated sensibilized animals have composed the control.

Control animals were administered by solving dose according to the similar scheme. The obtained results were statistically processed applying non-parametric confidence criteria. The exact Fisher technique (EFT) and U-criterion of Wilconson-Mann-Whitney were applied.

The anaphylactic shock death of infrasound exposed sensibilized animals was noted in 50-60% of cases. At the same time, in the control group 80-100% of animals have died within first 3 minutes after the solving dose administration (Figure 3.36). The high confidence level was obtained for desensibilizing activity of examined exposure parameters (Table 3.39). Table 3.40 indicates to the infrasound effect dependence versus the term of the sensibilization.

Most expressed shifts were noted in case of the exposure at days 20 and 30 after initial antigen administration. In case of the experiment tried at days 60 and 100, the confident infrasound effect in the allergic reactivity was not found. Tests tried at day 180 after the sensibilization has demonstrated the changed reaction of

exposed animals to the administration of solving dose of the alien albumin.

The infrasound exposure immediately before the sensibilization has not affected to the anaphylactic reaction development. Table 3.40 indicates that 72% of tested animals have died. In the control group the death rate was 67%. The exposure before the solving dose administration and within first 30 s after the provocation has induced the confident decrease of shock reaction severity in guinea pigs. The results of the experiment with the passive transfer of the immediate hypersensitivity state from exposed animals are provided by Figure 3.37. The recipient animals administered by exposed donor antigen have been found to have the increased number of animals reacted to the solving dose administration.

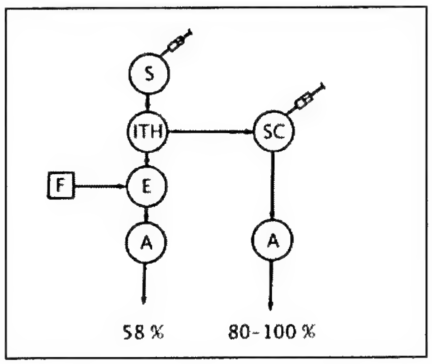


Figure 3.36 - Infrasound effect (10 Hz and 155-160 dB) in anaphylactic shock development after the active sensibilization
S - sensibilization, ITH - immediate type hypersensitivity state, F - exposure factor, E - exposure, A - anaphylactic shock development, SC - serum control

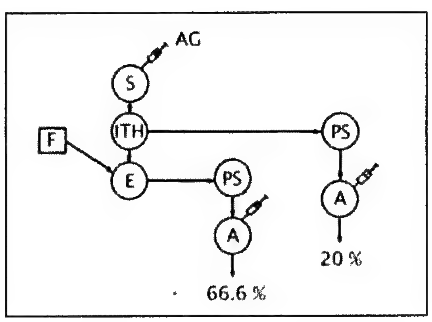


Figure 3.37 - Infrasound effect (10 Hz and 155-160 dB) in anaphylactic shock development after the passive sensibilization
PS - passive sensibilization. The legend is similar to that in Figure 3.36

Table 3.39 - Anaphylactic reaction vs. infrasound exposure conditions

Condition exposure	Anaphylactic reaction (on death criterion)		Statistical analysis	
	test	control	EFT	U-criterion
Before sensibilization	18/25	10/15	0.25	p > 0.05
before provocation	30/56	44/55	0.0081	p < 0.01
after provocation	8/13	15/17	0.086	p < 0.01

Note. Died/sensibilized animal ratio, B; p - probability of occasional discrepancy of experimental and control results.

Table 3.40 - Infrasound effects vs. sensibilization terms

Sensibilization term, day	Anaphylactic reaction (on death criterion)		Statistical analysis	
	test	control	EFT	U-criterion
22	1/5	7/10	0.09	0.01 < p < 0.05
30	8/16	10/13	0.32	p > 0.05
35	8/13	15/17	0.07	p > 0.01
60	6/8	5/7	0.32	p > 0.05
100	4/4	4/4	1.00	p > 0.05
180	3/10	3/4	0.16	p > 0.05
	30/56	44/55	0.0081	p < 0.01

Note. Died/sensibilized animal ratio, B; p - probability of occasional discrepancy of experimental and control results.

When concerning mechanisms of the revealed phenomenon, it should be noted that inadequate reaction has been caused by the factor of large dissemination in the natural environment. Alternatively to the ionizing radiation, the mechanical character of the initial action of the infrasound is obvious. It relates to the changed air pressure, tension and deformation changes in the exposed object; these factors are poorly investigated regarding initiation of biological processes.

The elaborated experiments with changed exposure conditions and passive sensibilization series certify to the fact that infrasound effect is the consequence of deviations induced in the specific part of the anaphylactic shock.

Thus, the analysis of literature references and original results certify to the presence of previously unknown biological phenomenon, which has manifested in the inadequate reaction to the alien albumin after the exposure to physical factors of both ionizing and non-ionizing character. The future development of this issue would be actual, because it will give the opportunity to develop the principally new ways of the immune system affecting to normalize the organism reactivity and to consider these data, when elaborating the hygienic assessment of the human environment.

3.13 Combined effects of microwave, infrasound and gamma radiation

The immune system is the very comprehensive physiological apparatus providing protection of internal homeostasis. This is the explanation of the peculiar sensitivity of this system to physical factors of the environment including ionizing and non-ionizing factors. The unfavorable effects of non-ionizing radiation can be realized at different levels and parts of the immune reactivity (see scheme).

Most labile and sensitive index of the immune status is the functional completeness of immune competent cellular systems. Physical environmental factors are able to change the perception of antigen irritation, antigen information transfer and effective activity of cells in case of weak exposure levels (Belonojko N.G., Vinogradov G.I., 1977; Vinogradov G.I., 1975; Vinogradov G.I., Dumansky Yu.D., 1974). The high sensitivity is also designated to autoimmune processes and non-specific natural resistance (Gabovich R.D. et al, 1979).

When elaborating the hygienic standardization, it is necessary to consider not only the immune index sensitivity but also the possibility of specificity of protective reactions to the radiation exposure of different origins and their combinations. At present time, it is firmly established that ionizing radiation would depress immune system at cellular level.

Health effects of non-ionizing radiation of microwave range are characterized by exposure intensity, wavelength and exposure time. The exposure at low power flux densities (PFD) of < 1 mW/cm^2 will increase the immune activity; for 1 to 10 mW/cm^2 microwaves, the information is contradictory.

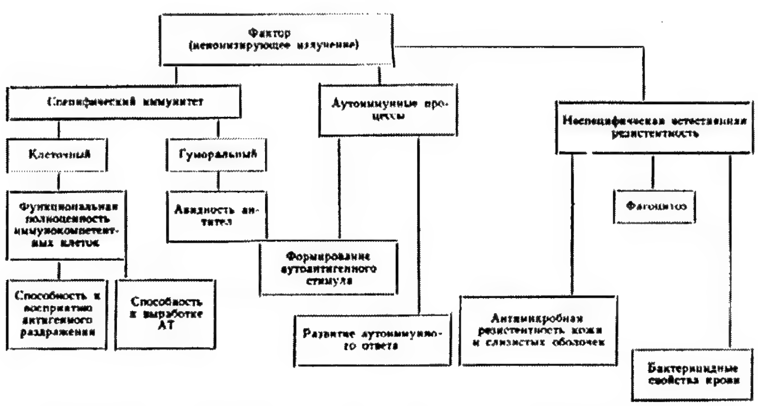


Figure 3.38 - Ionizing radiation effect realization in immune system

From the one hand, the depression of lymphopoiesis and immune competent cell function, the decrease of leukocyte cytophagous potential are established. The data on the unchanged humoral immunity are also obtained (Ivanov A.I., Tchukhlovin B.A., 1968). The decreased cellular response to infection was noted in rabbits together with the anti-infectious resistance weakening.

From the other hand, early publications certify to the opposite effect of microwaves for such PFD values. Guinea pigs were found to have the lymphopoiesis amplification, doubling of lymphocyte count in the spleen and lymph nodes. Similar results were obtained in rabbits. The amplification of neutrophil absorption and digestion functions, antibody production stimulation in case of typhoid vaccine administration, development of autoallergic processes, lysozyme titer and serum complement decrease were found. According to N.P. Zalubovsky and R.I. Kiselev (1973, 1978), single exposure at 2–5 mW/cm^2 has not affected the fatal microbial dosage dissemination in the organism.

The biological effect was significantly influenced by the wavelength and exposure time. The exposure at 1–2 mW/cm^2 (meter band) has decreased the absorption ability and motility of neutrophils; in case of centimeter and millimeter bands, such effects were not found.

The exposure time is very important for EMR effect realization for weak (10 to 50 $\mu W/cm^2$) exposure levels, which are able to stimulate quantitative and qualitative indices in lymphocyte systems and to amplify cytophagous activity of cellular elements of peripheral blood. The change of antigen content of tissues was found, which change has expressed via the new abnormal antigen quality and disappeared portion of normal antigens in case of 50 $\mu W/cm^2$ of chronic exposure. The antibodies found in experimental animals were directed to the cerebral tissue; 2–5 times decrease of the antibody titers was noted in the agglutination reaction (Vidal) and indirect hemagglutination.

The exposure to ultraviolet, light and infrared radiations can modify allergic skin reactivity (depending upon the intensity and exposure time). The ultraviolet depression of the contact hypersensitivity was obtained for wavelengths of 260 to 270 nm. The light exposure of skin can provoke photoallergic dermatosis, which are clinically similar to contact eczema and are related to immune reactions of the delayed type. The passive transfer of photoallergy is possible applying mononuclear cells.

Interesting results were obtained for laser radiation effects in immune activity of blood serum antibodies. Pulsed lamps and lasers were the sources of radiation: argon laser (λ = 488 nm and λ = 514.5 nm); cadmium vapor laser (λ = 441.6 nm); helium-neon laser (λ = 632.8 nm) and chemical HF-laser (2.7–3.2 μm). The immune analysis has demonstrated that laser radiation of different

wavelengths is able to change free immunoglobulin concentrations and to affect the activity of specific antibody totality, which certifies to the presence of specific photo-chemical effect of low intensive laser radiation of different wavelengths.

The low frequency acoustic oscillation effects in immune indices are poorly investigated. At the same time, this factor is widely present in the environment with average SPL of 100-110 dB (Shypack E.Yu., 1981). There are separate data regarding possible autoallergy processes in case of the infrasound exposure at 100-115 dB (Shutenko O.I. et al, 1979).

Possible stimulation effect is present for low intensive ionizing and non-ionizing radiation. The immune reactivity stimulation was found in case of microwave exposure of low PFD (Belonojko N.G., Vinogradov G.I., 1977; Vinogradov G.I., 1975; Vinogradov G.I., Dumansky Yu.D., 1974; Vinogradov G.I. et al, 1978). This finding is significant for combined effects of EMR and other physical factors of the environment.

According to the available literature, the microwave radiation can increase the resistance against ionizing radiation. It was demonstrated for immune reactions (Grigoriev Yu.G., Stepanov V.S. et al, 1984) and early hemopoiesis (Sevastyanova L.A. et al, 1974; Potapov S.L. et al, 1974). At the same time, the combination of effects of microwave and infrasound was found to be synergetic. The amplification of the response of different systems to the combined exposure to microwave and infrasound was established (Gabovich R.D. et al, 1979). These findings are important for hygienic standardization.

One of studies was devoted to combined effects of microwaves, gamma radiation and infrasound in immune indices of experimental animals.

Experiments were tried in 24 non-bred rats of both sexes (150-200 g body weights) and 10 Chinchilla rabbits (2.0-2.5 kg body weights). The following immune indices were examined: lymphocyte blast transformation reaction in peripheral blood (inclusion ED-thymidine in cell nuclei under the control of general leukocyte count), complement consumption reaction (animals were immunized by the multiple horse serum administrations before the exposure), auto plaque production reaction. The results were considered to be confident if the error probability (P) was less 5%.

Rats were exposed to microwaves (9.3 GHz, 200±20 μW/cm², 30 min/day, 8 days) with followed gamma exposure to 5.5 Gy (1.13 Gy/min dose rate). Control rats were exposed to microwaves (0.1 GHz, 1530 μW/cm², 60 min) and gamma radiation of the same dose. Rabbits were affected by single microwave exposure and followed infrasound exposure at 8 Hz and 115 dB within 47 min. Blood samples were taken before and after each exposure episode.

At the first stage of the study in rats, the statistically confident non-specific immunity effect was found for microwave exposure at

200 μW/cm². Table 3.41 indicates that microwave exposure has induced the increase of integral leukocyte count and lymphocyte blast transformation reaction stimulation. Simultaneously, the relative content of auto plaques was decreased. The followed gamma exposure has significantly amplified blast transformation reaction if compared to the control (gamma exposure only), where this reaction was depressed. Some differences against control were obtained for auto plaque number, which was doubled versus 5 folds increase in control. At the same time, the integral leukocyte count in the test and control groups was the same.

Table 3.41 - Immune index changes in rats exposed to microwaves at 200±20 μW/cm² combined with 5.5 Gy gamma radiation

Index	Before exposure	Microwaves	Gamma radiation	Microwaves and gamma radiation
Integral leukocyte count, thousands	12.3±0.9	16.3±0.7	1.8±0.3	1.9±0.3
Autoplaque number, %	4.9±0.5	1.84±0.60	20.7±5.4	10.7±1.5
Blast transformation reaction, stimulation index	5.42±0.46	6.4±0.4	3.13±1.1	10.10±2.75

The rabbit series has demonstrated the wobble reaction to the combined microwave - infrasound exposure if compared to separated exposure to microwave or infrasound. Table 3.42 indicates that blast transformation reaction was not found to be different for baseline, combined exposure and exposure to the single factor alone. However, the trend of the stimulation index decrease was noted in case of the combined exposure and microwave exposure, whereas the infrasound exposure has induced some increase of this index. The complement consumption reaction has been found to demonstrate significant differences for each factor effect in humoral immunity versus their combination. In case of single microwave exposure at 1530 μW/cm² and single infrasound exposure at 115 dB and 8 Hz, this index was confidently decreased; the combination of these factors has elevated the reaction level to the baseline (Table 3.42). If the infrasound exposure has double decreased the reaction level, the microwave exposure has reduced this level for 8 times.

Table 3.42 - Combined effects of microwaves (1530 μW/cm²) and infrasound (115 dB and 8 Hz) in some immune indices in rabbits

Index	Before exposure	Infrasound	Microwaves	Microwaves and Infrasound
Blast transformation reaction, stimulation index	1.22±0.30	1.76±0.50	0.98±0.10	0.95±0.15
Complement consumption reaction, cond. units of consumed complement	3.2±0.5	1.6±0.3	0.4±0.1	2.3±0.4

The low T-lymphocyte resistance to gamma radiation is well known; however, the preceding microwave exposure has resulted to strong increase of their resistance to gamma radiation.

Being the integral test of immune competent cell function, the blast transformation reaction dynamics certifies to the different qualitative state of the organism induced by microwaves and demonstrated after the gamma exposure. The mechanism and cause of this change are not known yet. It can be assumed that the obtained effect is the only one sign of general adaptation syndrome, which was probably formed after the microwave exposure. The auto plaque production reaction dynamics data confirm this viewpoint.

The microwave - infrasound combination has been found to have different significance of the preceding microwave exposure. The infrasound exposure has not induced confident changes of blast transformation and complement consumption reactions. At the same time, single exposure to each of these factors has induced shifts of indices, if compared to the baseline.

The peculiar interest is attracted to the complement consumption reaction. Results have confirmed the microwave-infrasound combination synergism. If the functional activity of lymphocytes corresponds to the microwave effect level (below the baseline and level induced by the infrasound), the number of antibodies found in case of the microwave - infrasound combination was 6 times higher than microwave level and only 1.5 times higher than infrasound level. It can be assumed that combination of several physical factors results to effects determined not only by parameters of each factor but also by the sensitivity of indices applied to evaluate reactions to these factors. In such case, the immune competent cells are more sensible to microwaves, whereas the humoral immunity is more sensible to the infrasound. This statement is confirmed by other data, particularly, the data on single infrasound exposure and infrasound-microwave combined exposure, where the autoallergic process development was established, whereas the microwave exposure attenuates such effect.

Thus, the elaborated studies indicate to the complexity of the assessment of combined effects of ionizing and non-ionizing radiations, which have different mechanisms of biological effect realization.

3.14 "Resonance" theory of LFAO effects in biological rhythms

A number of researchers (Guignard J.C., 1968; Johnson D.L., 1974; Pimonow L., 1971; 1976 et al) have assumed "resonance theory" for infrasound health effects. They consider the coincidence of infrasound frequency and own frequency of specific organ to

induce strong excitation of receptor apparatus, which results to the specific symptoms.

Human resonance frequencies are 5, 10 and 15 Hz (Johnson D.L., 1974). This resonance depends upon the mechanical impedance of the human body and muscular tone. Author has demonstrated that worse resonance effects were observed in the abdominal cavity.

D. Diekmann (1959) has demonstrated that "resonance" of the human body is in the range of 5 and 7 Hz. R.W. Stephens (1969), W.F. Grether (1971) have indicated to highest sensitivity at 5 Hz. R. Goermann (1969) has concluded that 4-6 Hz are the human body resonance frequencies. H.J. Seris (1969) has noted that the best coincidence is present for 4–10 Hz. Infrasound oscillations at < 10 Hz induce resonance in large internal organs (stomach, liver, heart, lungs) which was manifested by the pressure sensation in hypochondrium, chest and abdominal wall vibrations. At >10 Hz, unpleasant sensations in nasopharynx, urine bladder and rectum are possible. However, L. Pimonow (1976) has noted that in all "resonance" cases the oscillation conduction vs. frequency is the issue, rather than resonance itself.

A number of studies have correlated body vibration (in chest, abdominal wall, larynx etc) to infrasound and LFAO exposure via direct biomechanical resonance effect, which was justified by biodynamic model of the human body of concentrated parameter (Figure 3.39).

The concentrated parameter model of the human body can be applied to predict and to understand respiratory reactions to infrasound and explosion waves and to analyze the relationship of the chest wall and abdominal wall in case of such vibration (Gierke H.E. von, 1968; 1973; from Tempest W., 1976).

According to Gierke H.E. von, if the wavelength is much more than object size (human body), the acoustic pressure affects the body from all sides at the same phase, which provides the periodical body contractions. At the time of contraction, the abdominal organs shifts in the chest direction would occur and the tissue oscillation is present due to the air shifts in the body cavities. The largest cavity is the chest. The major oscillating mass includes abdominal organs, which are moved together; this movement results to contractions and attenuation of the air in lungs. Such effect was found for low frequency vibration, but LFAO affect not only the abdominal cavity and chest but also the air flow in the oral cavity, trachea and lungs i.e. "from inside and from outside", simultaneously. Therefore, the biomechanical system is more rigid against air oscillations if compared to vibrations and the major thoracic - abdominal resonance would be at 40–60 Hz (alternatively to 4–8 Hz for general vibration).

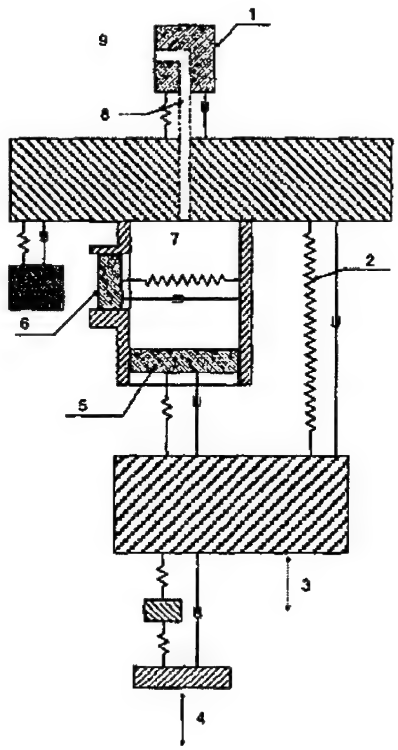


Figure 3.39 - The concentrated parameter model of the human body: reactions to long shock, vibration, explosion or infrasound
1 - head, 30 /s; 2 - spinal cord, 8 /s, which is critical for damages from + G_z;
3 - periodical force, shock, complete input resistance - applicable to sitting examinees, 4-6 /s; 4 - periodical force shock - applicable to standing examinees;
5 - abdomen, 4-8 /s; 6 - chest wall, 60 /s; 7 - lung volume; 8 - trachea;
9 - change of pressure and volume in lungs

Having in mind conceptual logic and usefulness of the concentrated parameter model of the human body, it should be underlined that it does not take into account neurobiological aspects of LFAO perception in sensorial systems (aural, vestibular response, propryoreception, visceroreception) as well as afferent and efferent formations of spinal cord and brain.

The vibration sensations in chest, abdominal wall and other body parts are apparently elaborated via extra-pyramid hyperkinesia.

The resonance considerations disagree to the statement that "the sensation of the internal resonance has disappeared within 3 hours" (Gavreau V.R., 1968). Thereafter the infrasound exposure, the author has felt very unpleasant sensations: "the whole sound and whole vibration were inside the body".

N.F. Izmerov et al, (1998) have considered that body part vibrations contain the important component correlated to infrasound effects in the brain including diencephalic structures.

Low frequency acoustic fields of the organism

All biological objects (including human) are continuously affected by LFAO originated from different natural sources. The evolution and life processes are affected by the background LFAO of 30-45 dB (Novogrudsky E.E. et al, 1989).

The biological objects are the sources of low frequency acoustic fields themselves. The combined functioning of different organs and systems results to a number of mechanical oscillations including low frequency oscillations. The dynamic system of low frequency acoustic fields generated by organs and systems of the body creates original (endogenous) low frequency acoustic field of the organism.

Low frequency acoustic oscillation sources are heart, respiratory organs, digestive tract, locomotor joints. Pregnant women also have fetal cardiovascular system producing low frequency acoustic oscillations. The integral acoustic field is the superposition of acoustic waves generated by all these sources.

According to A.M. Kirsanov (1971), I.P. Zamotaev et al (1974) and others, the frequency range of these oscillations is given by Table 3.43.

Table 3.43 - Frequency range of acoustic fields of the organism (Kirsanov A.M., 1971; Zamotaev I.P. et al, 1974 and other authors. Bioacoustics, p. 64)

Generation mechanism	Frequencies, Hz
Contraction and relaxation of ventricular myocardium	12.5 - 18
Blood vibration in case of rapid diastolic filling of ventricles	12.5 - 20
Opening and closure of semilunar valves	31.5 - 63
Opening and closure of cuspidate valves	80 - 100
Ist cardiac tone	125-160
IInd cardiac tone	22.5 - 1400
Vesicular breath	45 - 2800

The presence of elastic waves was noted at cellular level. At the time of the action potential propagation via the sciatic nerve, the neurolemma oscillations were noted (30 nm amplitude and 4 Hz frequency) (Frank G.M. et al, 1954). The nervous impulse propagation in octopus axon results to low frequency elastic cross waves (Levin S.V. et al, 1980). The cellular and molecular sources of low frequency elastic oscillations are assumed. For instance, theoretical calculations indicate to periodic oscillations of erythrocyte organoids can generate acoustic oscillations at 0.2 to 30 Hz (Brochard F., Lehnon E., 1975). These calculations have to be confirmed by the experiment.

Some studies have assumed the endogenous low frequency fields to be involved in the inter-cellular information transfer and different substance traffic (via microtubes), morphogenesis and synchronization of biochemical processes in tissues (Shnoll S.E., 1976; Gurvich A.G., 1991).

The LFAO exposure can theoretically increase the tissue shift amplitudes due to the interference of low frequency mechanical oscillations and acoustic oscillations of heart and other internal organs, which own frequencies are low (Kirsanov A.M., 1971; Berezovsky V.A., Kopotilov N.N., 1990). The recorded sound pressure levels originated from the heart contractions have reached 80–94 dB (Odintcov S.G., Kheymetc G.I., 1981). However, the power flux density of these mechanical oscillations is insignificant for biological tissues because of their positioning in the non-formed wave area of the main oscillation source (heart). Besides, the fluctuation of cardiac and respiratory rhythms prevents the oscillation interference for oscillating organs and acoustic oscillations affecting the body. Therefore, the interference maximum appearance in the body tissues is hardly possible (Table 3.44).

Table 3.44 - Biological rhythm frequencies

Human EEG					
EEG rhythms	α	β	Δ	θ	Arabadji V.I., 1992.
Frequency, Hz	8–13	15–35	0,4–4	5–7	
Amplitude, μV	70–100	5–30	50–500	10–30	
Rat EEG					
EEG rhythms	α	β_1 and β_2	Δ	θ	Bachurina T.I., 1974.
Frequency, Hz	8–13	13–20 and 20–30	2–4	4–8	
Human pulse rate: 1.25 Hz					Arabadji V.I., 1992.
Eye blinking rate in human ("optical closure") 0.2 - 0.5 Hz					Arabadji V.I., 1992.
Frequency range of chest and abdominal cavity oscillations in human (resonance frequencies) induced by LFAO					
40 - 60 Hz					Gierke H.E. von, 1974
5 - 15 Hz					Jansen G., 1974
4 - 8 Hz					Novogrudsky E.E. et al, 1989
Basic frequencies of own oscillations of human body and body parts, Hz					
Posture: - laying 3 - 4 - sitting 4 - 6 - standing 5 - 12	Chest 5 - 8 Abdominal cavity 3 - 4 Head 20 - 30 Bent arms 5 - 8				«Bioacoustics», 1975 (edited by V.D. Ilyichev)
Resonance frequencies for the whole body and body parts in case of *general vibration* exposure					
4 - 15 Hz					Frolov K.V. et al, 1989 (from «Bioacoustics», p. 59)
Frequency range of own oscillations of the human body in case of LFAO exposure					
> 10 Hz					Paranko N.M., Madatova R.B., 1990; Romanov S.N., 1991; Guignard J.C., 1968.
"Resonance" frequencies, Hz					
Vestibular apparatus 0.5 - 1.5 Stomach 2 - 3 Heart 6 - 7 Brain 20 - 30 "Information flows" in brain 9 ± 0.5 Hz					Karkishenko N.N., 2001

Taking into account active properties of some biological tissues, low frequency acoustic oscillations can be the physiological irritators. Obviously, the organism reactions to such stimulation should be determined by the energy distribution in organs and tissues and by the characteristics of the external low frequency acoustic field. If the sound pressure amplitude is decreased to the level of external noises, the significance of physical effects is progressively decreased and the leading role belongs to spectral and temporal parameters of low frequency acoustic oscillations.

Taking into account above mentioned considerations, the "resonance" theory of infrasound and LFAO health effects in human and animals is not scientifically justified.

3.15 Infrasound and LFAO as a mean for non-lethal weapons (NLW)

In 2001, two papers have been published in the USA and Russia, which papers have surveyed data regarding health effects of acoustic oscillations. The issue is the development of so-called "non-lethal weapons" applying infrasound and LFAO.

N.N. Karkishenko (2001) answers to the question - What is non-lethal weapon? - as follows.

Non-lethal weapons are the damaging means able to inflict functional destruction of arms, military equipment and military personnel; such weapons use SHF of laser radiation, non-coherent radiation sources, acoustic ultrasound and infrasound radiation, chemical substances, biological or biotechnological agents etc.

The non-nuclear and nuclear weapons are designated to destroy military equipment and personnel (so-called "hard kill"). Damaging NLW effect is directed to non-destructive (soft kill) damage resulting to the functional disorder of military equipment, arms and transient dysfunction of military personnel without serious health harm.

However, we are far from the idea that NLW will be seriously involved in future wars. Large wars (if happened) will need other forms and methods. Nevertheless, NLW is already applicable for neutralization of single terrorists or terrorist groups, for anti-terrorist actions and local military conflicts.

Military analysts consider NLW application as the kind of technological sanctions during both military operations and prevention or forcing states intending to apply chemical, biological or nuclear weapons.

The example of military technological operation can be the application of specialized ammunitions to destroy electric power supply lines (Electric Power Distribution Munition, EPDM), which were used by the USA in Gulf war, Bosnia, and Kosovo; these ammunitions are equipped with long electricity conducting carbon fibers, which cause short circuit when contacting electric lines. The electric power supply recovery was very complicated, because fibers have been again contacted to lines in case of any wind. The complete removal of fibers has required the long and heavy work in the significant territory.

The hydroelectric power station dysfunction can be done via two ways: application of chemical agents changing the water viscosity with consequent

change of technological parameters (pressure, flow speed, etc) or the application of polymer compounds, which can jam the turbine vanes. Such actions would be very significant in countries having major hydropower supplies.

The moral and legal issues should be thoroughly considered, when NLW is concerned. 1972 Convention (ratified by the USA in 1975) on biological weapon ban can be interpreted as the exclusion of specialized ingredients able to make tank armor and artillery metal to be fragile, or to spoil fuel and lubricant materials. Recently adopted convention on routine weapons does not note non-lethal technologies but its statements can be revised. For instance, the proposal is issued on the exclusion of laser radiation to blind the opponent or not-involved persons.

The foreign literature uses the term of "non-lethal" as well as "disabling", "less-than-lethal", "anti-material", "low-collateral" etc. The term of "non-lethal weapon" can be hardly successful. In Russia, together with informal terms of "non-lethal/non-fatal weapon", they use "non-fatal effect weapon" (NFEW), "non-lethal kinds of weapons" (NLKW) and also "non-traditional weapon" or "weapon of non-fatal effect". The most exact terms would be "disabling" and "soft kill", which means "soft" non-destructive damage of military equipment and personnel. Nevertheless, both American and Russian references use the term of "non-lethal", which will be used hereafter.

NLW development is essentially sound at present time. It is closely related to recent problems of peace keeping, police operations and humanitarian missions elaborated by armed forces (for instance, in Bosnia, Somali, Rwanda and other countries), where it is necessary to make effective military operations without excessive losses of manpower and materials of the opponent and to exclude the local conflict escalation, which is possible in case of the application of routine weapons and, essentially, nuclear weapons.

To disable arms, military equipment and manpower, a wide range of technological advances is evaluated in the USA.

From the military viewpoint, NLW can be subdivided into two conditional categories: NLW designated to disable arms, military equipment and logistics and NLW designated to be applied against manpower, though a number of non-lethal technologies are applicable in both cases.

NLW development in the USA was tried by armed forces, some military laboratories, ARPA, and industrial companies. In the US Army, the development is leaded by ARDEC, NJ, in the framework of Low Collateral Damage Munitions, (LCDMCoM) program. The goal of this program is "to get more flexibility in future conflicts, to increase tactical abilities above these provided by shooting arms and explosive ammunitions, to get the low side harm and to minimize manpower losses".

The program includes more than dozen of different disabling technologies. The significant research was contracted by ARPA, as well as by Livermore and Los-Alamos National Laboratories, Philips laboratory (USAF) and Harry Diamond laboratory (US Army). One of seven research priorities of US Special Operations Command, USSOCOM is NLW development.

Routine ammunitions of different weapon systems can be modified to decrease their damage effect to the level excluding the lethal outcome. The well known application of rubber, wooden and plastic shotgun bullets and ammunitions with rubber or elastic elements dissipating energy in the target ("beanbag").

A number of transient disability means is based upon the electric charge including contact means (stun guns, gloves, networks) and distant means

(distant discharge, arrow wired elements, capacitor bullets etc). The electric discharge will deafen or deprive the consciousness for 1-10 min.

The basics of non-lethal weapon application include the shift of the "information support" concept to the "information aggression" or even to the "information war". The information war weapons include information media and technologies applied for rapid and hidden application in military or civilian information systems of the opponent to destroy its economy, defense readiness and military abilities. According to American specialists, the information war became possible because of "cybernetic revolution" resulted to the implementation of different information systems based upon electronic means.

Recently, the foreign military press has discussed the issue of holography effects in human psychics. Particularly, during the "Hope Revival" operation in Somali, American specialists have tried to make laser projections of Islamic prophets in the cloud surface; these images have advised their adherents to stop resistance ant to come back home. In 1 February 1993, American mariners have seen the image of human face (~ 150 x 150 m sizes) during the sand storm near Mogadishu (Somali). Witnesses of this phenomenon have been seriously impacted.

This example indicates that new kinds of NLW will be designed basing upon modern information technologies rather than physical and chemical principles (Karkishenko N.N., 2001).

Drug prophylaxis (Karkishenko N.N., 2001)

The most serious effect of electromagnetic and infrasound exposure (EMIE) is the seizure syndrome. Therefore, the application of anti-seizure and anti-epileptic agents is the obligatory in case of EMIE.

The ability to mitigate or attenuate seizures is specific to such agents like barbshpurotes, different tranquilizators, and soporific agents, bromides, narcosis agents and some others. Some agents of specific anti-seizure activity and efficiency in case of seizure reactions, seizure anti-toxins (strychnine, corazolum), infectious diseases (tetanus) are also applicable.

Epilepsy effective agents (Phenobarbital, Metabarbital) are essentially applicable; diazepam and nitrazepam are useful and clonazepam is most applicable.

Table 5.1 - Effective concentrations of some anti-epileptic agents in the blood plasma for therapy of NLW effects

Agent	Effective level (μg/mL)	Upper border of effective level (μg/mL)	Intoxication level (μg/mL)
Carbamazepin	4-10	7	>8
Primidone	8-15	10	>12
Difenin	10-20	18	>20
Phenobarbital	10-40	35	>40
Ethosuccimide	50-100	80	>100
Valproate1	50-100	80	>100

Nikolay Karkishenko, Russian pharmacologist has included a special chapter devoted to NLW and infrasound, particularly (Karkishenko N.N., 2001). The other paper belongs to Jürgen

Altmann, German physicist (Altmann J., 2001); this paper discusses acoustic weapon perspectives in details.

It is necessary to note that the first paper is full of unjustified references to expressed health effects of the infrasound ("energy effect", "information effect", "resonance effect"), which effects induce "... pain, cramps, intestinal spasm, cardiac arrest, and death". According to N.N. Karkishenko, "... the acoustic exposure at 9±0.5 Hz induce strong effects in information flows in the brain (?!) even in case of moderate intensity levels, which disturbs intra-central relationships and induces unexplained fear, panics, spatial disorientation, and disorders of the pulse rate and breath rhythm up to the complete stop".

The second paper, alternatively, provides reliable and balanced scientific evidences regarding infrasound effects in human organism, which evidences seem to be basic and absolutely valid.

Taking into account that the problem of the development of acoustic means, so-called NLW, is not the issue of the present monograph devoted to the assessment of biological effects of infrasound and LFAO for hygienic purposes, the paper of Jürgen Altmann are provided by the Addendum of the present monograph.

Chapter 4 HYGIENIC REGULATION OF LOW FREQUENCY ACOUSTIC OSCILLATIONS

4.1 Maximum permissible levels (MPLs) of the infrasound

The analysis of results provided by previous chapters certifies to the fact that low frequency acoustic oscillations are the ecologically important factors of the human environment. The investigation of their health effects and effect mechanisms is of more significance when developing issues of ecological safety and hygienic standardization criteria.

According to Samoylov V.O. et al (1994), at first seconds of the stimulation, the afferent responses of mechanical receptors of different types occur under the exposure to low frequency acoustic oscillations. Pulsed reactions of mechanical receptors are regularly dependent on acoustic oscillation parameters. The analysis of stimulation-effect ratios for all mechanic sensory systems has given the opportunity to conclude on the *major* importance of power flux density to induce acoustic oscillations sensory responses in all mechanic sensory systems. The magnitudes of generalized reactions of the whole organism are also proportional to power flux densities of low frequency acoustic oscillations.

For low frequency acoustic oscillations, the power flux density is basically determined by the oscillating movement of the media particles. Regularly, the electric reactions of mechanic receptors are proportional not to the sound pressure but to the value of oscillating movement of the air media particles. The high correlation level was established for afferent response values versus the oscillating movement amplitude. Therefore, the very oscillating movement is the effective parameter of the acoustic stimulation in mechanic sensory systems of the organism. Its magnitude is most informative for low frequency acoustic exposure and it determines the mechanical energy absorbed by biological objects. Thus, the ecological importance criteria of this factor should be based upon the energy characteristics of the affecting acoustic stimulation.

Inasmuch, the national practice of hygienic standardization, the acoustic exposure regulation is still based upon the sound pressure level (Karpova N.I., Malyshev E.N., 1981; Suvorov G.A. et al, 1981; Shypack E.Yu., 1981; Hygienic Standards... 1982; Suvorov G.A., 1983; Sanitary Standards... 1989). Such approach does not consider the inter-position of acoustic oscillation sources and biological objects, which often are in the area of non-formed wave of low frequency acoustic emitter. In this area the value of power flux density is predominantly determined by the oscillating movement

amplitude of the air media, so the assessment of organism response reactions depending on the sound pressure level should not be recognized as the correct one. Such assessment does not take into account the leading role of the oscillating movement, which determines power flux density of acoustic oscillations affecting the organism. More adequate approach for low frequency acoustic oscillation standardization according to energy characteristics is impeded by unclear mechanisms of low frequency acoustic oscillation effects as well as the obstacles of the instrumental measurement of the oscillating movements and power flux densities.

Acoustic intensity measurement techniques are rarely applicable by national hygienic practice, which is basically related to the absence of the assured equipment. However, the interest to these techniques is present in Russia and abroad, which was reflected by first monographs on the intensity measurements and vector phasic analysis of low frequency acoustic fields (Fahy F.J., 1989; Gordienko V.A. et al, 1989). At the same time, the modern biological acoustics does not have any single technique for simulation of low frequency acoustic oscillations and quality assurance methods of the technique assessment are absent, which results to significant differences of experimental results obtained in different laboratories. Many researchers are not sufficiently familiar in physics and biophysics, which causes the underestimation of fundamental regularities of viscous-elastic body mechanics.

At present, the scientific reports predominantly provide the phenomenological descriptions of the observed effects. The acoustic frequency, sound pressure level and exposure duration are usually provided. However, other conditions necessary to get the correct reproduction of the experiment are not determined including: acoustic chamber parameters, biological object to source distance; these parameters determine the power flux density value. Many studies do not give data to justify the conclusion confidence, including: statistical homogeneity of the sample, number of measurements done to draw the functional dependencies, methods of the result processing. The unattended description of experimental conditions as well as the absence of confident data to confirm conclusions drawn reflects trends of search for specific effects of low frequency acoustic oscillations; this search involves hidden or even clear deviation to psychics, parapsychology and other directions of so-called "bioenergetics" (Samoylov V.O. et al, 1994).

When assessing effects of the low frequency noise and infrasound in the environment, the human protection is the first priority of concern. The leading role of this issue consideration belongs to the hygienic standardization which is authorized to establish justified maximum permissible levels of the infrasound and low frequency noise as the harmful industrial factor.

At the International Infrasound Colloquium (Paris, CNRS, 1973) Nixon C.W. has recommended 120 dB sound pressure level as the upper limit for 18-20 Hz frequency to protect audition organs; the decreasing frequencies correspond to 3 dB/octave decrease. However, the practical interest involves data on the health effects of the infrasound as well as the workability effects in the industrial environment. Therefore, proposed infrasound limit can be permitted for short-time (5 min) exposure only. In case of the long-term infrasound exposure the limit should be lowered.

The necessary basis of the human protection against infrasound includes criteria reflecting qualitative result of the whole organism effect. To create favorable occupation conditions, the infrasound assessment criterion should be similar to that for noise assessment i.e. the health preservation. It means that harmful infrasound effect should not manifest or should insignificantly manifest in case of systematic exposure of human within many years.

N.I. Karpova and E.N. Malyshev (1981) have proposed the theoretical predisposition of "energy similarity" or "similar energy" rule to justify quantitative infrasound assessment technique; for the first time, this rule was used by C.W. Nixon and D.L. Johnson (1973) to justify standards. It is known that functional health changes can manifest after specified "dose" of the sound energy absorbed in the body. The "equal energy" rule presumes that the quantity of the sound energy inducing some functional health changes is always constant for any octaval strip of the standardized band. Such assumption is proper if the conditions of the sound propagation and their temporal character are similar. The upper frequency determining the range of this rule applicability is limited by sound oscillations, which wavelength is at least 4 times higher than basic anthropometric signs or maximal sizes of some elements and receptors having the specific sensitivity to the sound oscillation exposure.

Practically, the quantitative theory of noise assessment is applicable to infrasound and acoustic bands of frequencies i.e. for 1 Hz to 8,000 Hz. Thus, this theory provides the single methodological approach to the assessment of the infrasound and aural sound as a whole. To determine numerical values of noise limit, the following formula is proposed for octaval frequency bands of 1-8,000 Hz:

$$Li_{add} = L_b - 10\ lg\ f_i/f + 30\ (dB),$$

where Li_{add} the maximum permissible level of the sound pressure for octaval band i; L_b is the basic level of the sound pressure corresponding to the limit spectrum (LS) in the octaval band of average geometric frequency of 1,000 Hz; this value depends of the human positioning place; f_i is the average geometric frequency of the present octaval band where the limit value is assessed; f is the average geometric frequency of the first octaval band of 1 Hz, which is the point of relative positions of other octaves.

For instance, the basic limit spectrum, L_b, established for the workplace by State Standard, GOST 12.1.003-76 and Sanitary Standard No. 1004-73

for octaval band of average geometric frequency of 1,000 Hz is equal to 80 dB. Applying this value to the formulae, the simplified expression for maximum permissible limits of the sound pressure for octaval frequency bands is as follows:

$$Li_{add} = 110 - 10\ lg\ f_i/f$$

Limit spectra calculated using this technique are shown by Figure 4.1 (from Karpova N.I., Malyshev E.N., 1981). Given formulae are applicable for industrial conditions to calculate maximum permissible levels, when the noise exposure is prolonged for the whole occupational shift, i.e. 8 hours. In case of the decreased exposure time, the "energy similarity" rule requires the increase of permissible sound pressure levels. For instance, if the exposure time is increased or decreased for 2 times, the sound energy amount should be decreased or increased for 2 times, respectively. When expressing this rule via sound pressure levels, it is proper to say that the decrease of the harmful factor exposure time (for 2 times, for example) results to 3 dB increase of its limit value. Same procedure is applicable in case of each 2 times change of the exposure time.

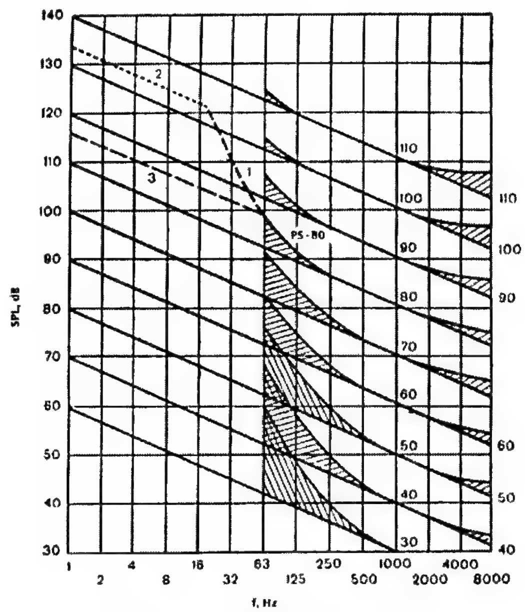


Figure 4.1 - Limit spectra of noise

PS-80: according to GOST 12.1.003-76; 1 — PS-80 extrapolation; 2 — recommended by Nixon C.W. (1974); 3 — recommended by N.I. Karpova and E.N. Malyshev

The calculation formula with correction for the exposure time is as follows:

$$Li_{add} = 110 - 10\ lg\ f_i/f + \Delta L_t\ (dB),$$

where ΔL_t is time exposure correction, $\Delta L_t = 10\ lg\ t_s/t_b$, t_s is the shift duration and t_b is the noise exposure per one minute of the shift.

Numerical corrections are provided by Table 4.1.

Table 4.1 - Time exposure corrections

t_b, min	480	240	120	60	30	15	8	4
ΔL_t, dB	0	+3	+6	+9	+12	+15	+18	+21

When analyzing limit spectra calculated according to this technique, it is visible that the frequency change (from high to low frequencies) results to the increase of their values proportionally to 3 db/octave. When comparing these values to the effective standards, one can find that limit spectra values are completely the same for the frequency range of 250—2000 Hz. For high frequency range, the differences are insignificant (1—3 dB). At low frequencies, the difference of limit spectra is started from 125 Hz (3 dB difference); the next octave (64 Hz) is specific to 7 dB difference. These differences would strengthen existing standards in the low frequency area.

Thus, in 1970th - 1980th the technique of the quantitative assessment of the industrial noise was the single methodological approach to the infrasound standardization as same as for the aural noise, taking into account their biological effect peculiarities.

Basing upon the literature data and original results of physiological hygienic and experimental studies of N.I. Karpova and E.N. Malyshev (1981), the following numerical values (see Table 4.2) were recommended as the octaval maximal permissible spectrum of low frequency and infrasound oscillations at workplaces.

Table 4.2 - Octaval maximal permissible spectrum of low frequency and infrasound oscillations at workplaces

Average geometric frequencies, Hz	63	31	16	8	4	2	1	0,5
Sound pressure levels, dB	99	102	105	108	111	114	117	120

According to N.F. Izmerov et al (1998), major research directions o improve infrasound hygienic standardization have to include following aspects:

- Hygienic assessment of biologically important parameters of the infrasound taking into account the concurrent vibration and acoustics factors like low frequency noise and vibration, the exposure duration effect, and the intermittent and continuous mode of the infrasound exposure;
- Health evaluation including morbidity, psycho-emotional condition, and cognitive function basing upon physiological, psycho-physiological and sociological studies (questionnaire polling) and applying modern techniques of the mathematical statistics for computerized data processing (combined influence of factors can be specified using multiple correlation regression analysis, routine correlation, factorial analysis, dispersion and discrimination assessments etc.) to reveal the factorial importance of the infrasound within the integral effect of industrial and environmental factors;

- Experimental volunteer studies of isolated and combined effects of the infrasound and other vibration and acoustics factors to get the quantitative assessment of the subjective perception, functional systems and psycho-emotional status;
- Experimental animal studies to obtain quantitative assessment of the infrasound in biological effects dynamics taking into account indices of vestibular and audition analyzers, neuro-humoral regulation and some homeostasis indices as well.

The precondition of the infrasound hygienic standardization is the choice of objective criteria giving the opportunity to consider qualitative health changes and to differentiate such conditions like fatigue and functional changes because the clear pathology is not applicable as the harm criterion.

However, the Russian and foreign references survey demonstrates that the single opinion regarding infrasound exposure consequences is absent: some researchers think that infrasound is specific to the expressed biological activity whereas others note that infrasound effects are strongly overestimated.

It should be noted that both opinions are justified for high infrasound levels and very short exposure times. Tempest W. (1976) has described results of the human infrasound exposure to 100-125 dB and 125-137 dB with frequencies of 2-5 Hz, 5-15 Hz and 15-20 Hz (Table 4.3).

Different subjective reactions were found in this case. For instance, the exposure to 100-125 dB was observed to have the pressure sensation in ears, obstructed swallowing, mild short-time headache. The increase to 125-137 dB at 5-20 Hz has included symptoms of abdominal vibration, nausea, middle ear pain, obstructed movement, lacrimation, fear feeling accompanied by shiver and sweating, but the repeated exposures has resulted to the symptom decrease i.e. the habituation has occurred.

Table 4.3 - Infrasound exposure in humans (Tempest W., 1976)

System, function	Tolerance borders and maximal effect
Hearing, Sound pressure perception	For <150 dB level 30 minute exposure is consider to be safe; mild shift of audible range is observed
Tympanic membrane	Ear pressure sensation for 130 dB; tympanic membrane retraction started from 120 dB
Middle ear	At 20 Hz, the pain threshold is 145 dB; at 4-5 Hz the pain threshold is 165 dB
Speech	Speech modulation since ~ 130 dB and increased with the level; for 150 -154 dB, the speech modulation is significant but does not decrease the speech distinction at small distance
Vestibular apparatus	No effects for <155 dB
Breathing	Rhythm change at 130 dB

It was established that the reaction time for the test is expanded if the infrasound level is above 110 dB; the recognition of digits and other operator activities is worsen for 120 dB at 7-10 Hz. For 140

dB (30 minute exposure to 15-20 Hz frequency band), the 14-17 dB shift of the aural threshold has occurred with rapid recovery thereafter.

Multiple exposures to pulsed noise of the supersonic aircraft (170 dB) do not affect the aural function. The tympanic membrane rupture occurs for ~ 187 dB (Tempest W., 1976).

The provided data indicate to the inapplicability of the infrasound effect criteria in case of the short-time exposure to high and extremely high levels, when doing the hygienic standardization. However, these data are of obvious interest because they provide information on the infrasound effect peculiarities in the specified rage o the sound pressure.

The accumulated data on the infrasound health effects have given the opportunity to make the conditional subdivision of its effects from fatal ones to very mild effects with unclear response. The first attempt of such subdivision into four groups was tried at 1973 Paris Colloquium (Pimonow L, 1974; Johnson D.L, 1974).

These groups of infrasound health effects, L. Pimonow (1973, 1976), are specified as follows:

I - infrasound of > 185 dB, which is of fatal danger (the variable pressure of such levels can induce pulmonary alveolar rupture);

II - infrasound of 140 dB to 172 dB, which 2 minute exposure is tolerable for healthy human;

III - infrasound of 120 dB to 140 dB, which is able to induce mild physical disturbances and fatigue in case of many hour exposures;

IV - infrasound of < 120 dB, which is not health harmful if its exposure time is less than several minutes; reactions of the long-time exposure are the subject for future studies.

Similar grouping are provided by A. Stan (1974) as follows: 180-200 dB is the fatal danger range; 150-180 dB is the range of clear dangerous effects; 140-150 dB at 0.1 Hz and 105-150 dB at 63 Hz is the range of dangerous effects; < 105 dB at 63 Hz and < 143 dB at 0.1 Hz are the ranges of the significant effect absence.

Thus, the averaged border of the infrasound health effect threshold is in the area of 112 dB at 31.5 Hz up to 140-143 dB at 0.1 Hz. A. Stan (1974) has proposed the graphic interpretation of infrasound effect ranges (Figure 4.2).

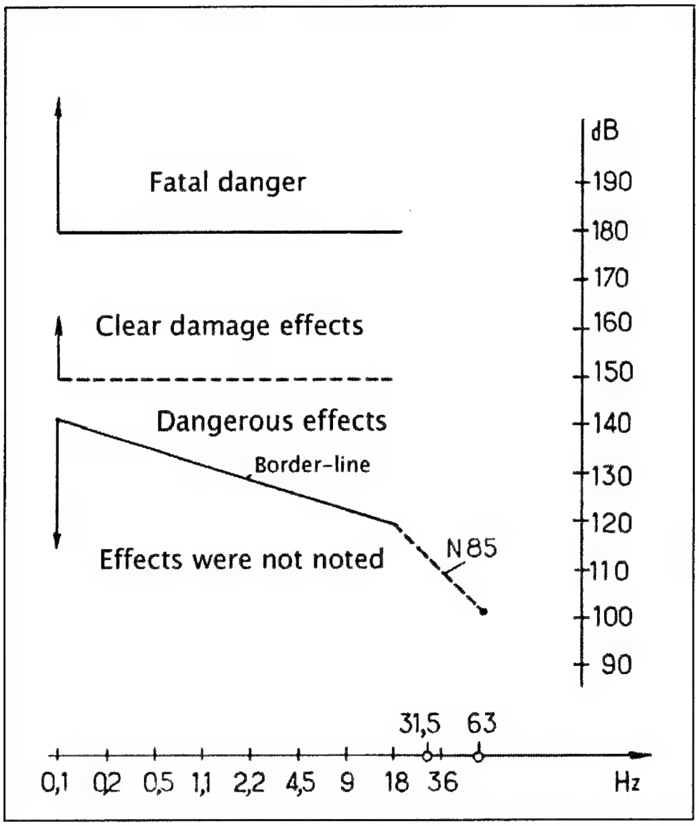


Figure 4.2 – Zones of the limit levels of the "energy" LFAO exposure in biological objects (from Stan A. and Johnson D.L.), accepted by the majority of 1973 Paris Colloquium members (Pimonow L., 1976)

When evaluating infrasound effects in human, different limit levels were proposed and deceased as the data were accumulating.

At 1-20 Hz range, the limit noise levels considered to be permissible within short-time (8 minutes) exposure are 150 dB at 1 Hz to 7 Hz, 145 dB at 8 Hz to 11 Hz and 140 dB at 12 Hz to 20 Hz, Gierke H.E. et al (1975), (Figure 4.3).

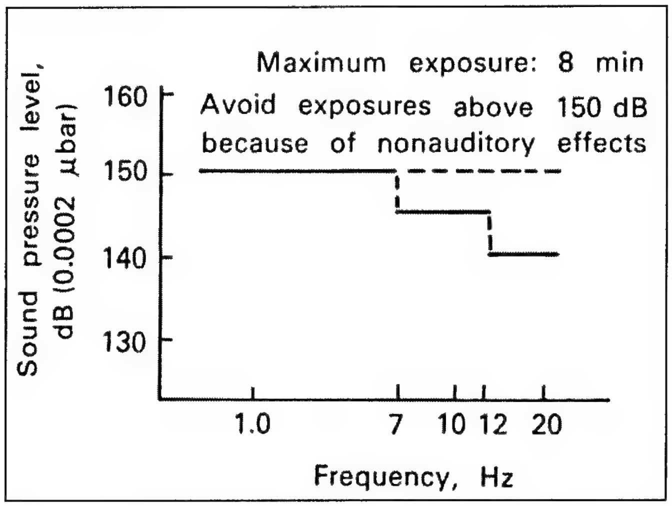


Figure 4.3 – upper tolerable infrasound levels
(von Gierke H.E., Nixon C.W., Guignard J.C., 1975).

These values are related to the discrete frequencies or octaval bands with centers around these frequencies. Maximal duration of the exposure is 8 minutes in case of 16 hour intervals between exposures. If good quality ear inserts are wear, the permissible level can be increased for 5 dB for the same time of the exposure. The infrasound exposure to > 150 dB should be avoided, because general non-aural reactions occur in such case even if best hearing protection is applied.

In the range of 20-100 Hz, the approximate limit levels for both discrete tones and for octaval bands are equal to 135 dB in case of single daily exposure of 20 min duration. This permissible level can be increased to 150 dB with the same duration, if good quality ear inserts are wear. The value of 150 dB is established if subjective extra-aural sensations are minimal.

N. Broner (1978) has provided the summary of recommended permissible infrasound levels in case of the short-time exposure at frequencies below 5 Hz: 140 dB (whole body); 166 dB (breath functions); 130 dB (aural and vestibular systems); 120-130 dB (physiological effects and workability); 120 dB (discomfort sensation).

Maximal permissible levels of different infrasound exposure duration are given by C.W. Nixon (1974): 145, 138, 135, 132 dB at 1, 5, 10, 20 Hz, respectively (1 hour exposure); 136, 129, 126, 123 dB (8 hour exposure); 131, 124, 121, 118 dB (24 hour exposure);

the proposed 24 hour infrasound limit is approximately equal to that of 75 dB "A" (Table 4.4).

Table 4.4 - Upper tolerable sound pressure levels (dB) which should not be exceeded to avoid hearing damage
(Nixon C.W., 1974)

Exposure duration	Frequency, Hz			
	1	5	10	20
8 minutes	150	150	145	140
1 hour	145	138	135	132
8 hours	136	129	126	123
24 hours	131	124	121	118

R.D. Gabovich et al (1979) have demonstrated the expressed infrasound influence in experimental animals; 90 dB intensity was considered to be the threshold one and 115-135 dB intensity has induces the expressed pathology. N.I. Karpova et al (1979) have noted that 100 dB infrasound has not practically changed the health of human and animals, whereas most dramatic functional changes are induced by 135 dB at 10 Hz.

N.F. Izmerov et al (1998) have analyzed original data and literature references and provided general grouping of infrasound biological effects (Table 4.5).

Infrasound experimental studies done by A.S. Nekhoroshev et al (Nekhoroshev A.S., 1986; Nekhoroshev A.S., Glinchikov V.V., 1991, 1992; Nekhoroshev A.S., 1998) have provided the following borders for health effects (see Table 4.6).

Table 4.5 - Major objective and subjective signs of the infrasound exposure and grouping according to its harm, danger and health risk zones
(Izmerov N.F. et al, 1998)

Risk zone	Frequency. Sound pressure level. Exposure.	Grade of harm and danger	Effects
1	2	3	4
I Fatal level zone			
	180-190 dB	-	Fatal effect (pulmonary alveolar rupture)
II Extreme effect zone			
	0-20 Hz <140-150 dB 90 s	4	Pressure sensation in the middle ear
	50-100 Hz > 154 dB 2 minutes		Headache, dyspnea, caught, hazed vision, strong chest pressure sensation, salivation, swallowing pain. Symptoms of the tolerance limit.
	100 Hz discrete frequencies 153 dB 2 minutes		Nausea, giddiness, discomfort, skin redness
	60 Hz 157 dB 2 minutes		Caught, strong chest pressure sensation

1	2	3	4
	73 Hz 150 dB 2 minutes		Dyspnea, salivation, swallowing pain, giddiness
	0-150 Hz up to 145 dB 2 minutes		Chest vibration sensation, mouth dryness, breath rhythm change, general fatigue, unreal false sensations. Below the limit of voluntary tolerance.
III High health risk zone even for periodical exposure			
	1-20 Hz 140-145 dB	3, 4	The jet engine work induces (in personnel) the chest and abdominal percussion; the state of sea disease, vestibular disorders including: static kinetic disturbances, sensorial disorders (giddiness) and vegetative disorders (nausea). The long-time exposure is specific to asthenia, general fatigue, mental workability decrease, irritability, insomnia; mental disorders due to anxiety and uneasiness.
IV High health risk zone for short-time exposure			
	2, 4, 8, 16 Hz 134, 129, 126, 123 dB 15 minutes	3,2 - 3,4	Subjective sensorial somatic vegetative discomfort: nausea, giddiness, pressure and massage of tympanic membranes, fever-like body tremor, pains in chest, temples, headaches, eyes. Salivation, anxiety. Transient numbness of the palate and facial skin (of sensorial cortex origin, apparently), voice modulation (of limbic origin). In general, these signs give the opportunity to establish the syndrome of infrasound (hypothalamic, diencephalic) crisis. Objective reactions: middle ear mucous hyperemia, decrease of static kinetic stability, vestibular vegetative para-sympathic effects (decrease of SAP, PR etc.), expressed decrease of CNS activation on the inter-hemispheric asymmetry coefficient. Increased reaction of the aural analyzer with increase of the infrasound frequency; increased reactions of vestibular apparatus, sensorial reactions and CNS reactions with infrasound frequency decrease
	10 Hz 135 dB 15 minutes	3, 4	Expressed sensorial somatic vegetative discomfort: headache, giddiness, oscillation and pressure of the tympanic membrane, internal organ vibration sensation, mouth dryness, breath complication
V Expressed progressing health risk zone			
	110 - 120 dB	3,2 - 3,3	Several minute exposure is out of health risk. Longer exposure can induce late effects in vestibular and aural analyzers and other body systems as well.
	2, 4, 8, 16 Hz 115 dB 1 and 5 hours	3,2	Interfering and irritating action, moderate infrasound discomfort: sleepiness, headache, ear pressure sensation, body vibration sensation. Complains increase with infrasound frequency decrease. Unfavorable influence in a number of physiological indices. Confident correlation to the expressiveness of the subjective perception and vegetative stabling and other indices of the functional body status.
VI Moderate health risk zone essentially with combination to other factors			
	16 Hz 105 dB 1 hour	3,1 - 3,2	Complains to interfering and irritating action (63% to moderate action and 13% to strong action), giddiness (20%); nausea, irritability, sleepiness (15% each complain); whistling in ears, headache (10% each complain). Objective findings: attention decrease, static kinetic stability decrease, PR decrease; expressed decrease of the functional CNS activity (inter-hemispheric asymmetry coefficient).
	8, 16 Hz 100 dB 1 hour	3,1	Complains to throat discomfort, caught, noise and pain in ears, flaccidity, sleepiness, low attention. Significant physiological changes are not found.
	90 - 100 dB	3,1	Short-time exposure is out of the health harm; daily exposure can induce complains, discomfort etc. Significant increase of the spontaneous abortion incidence (from 11 to 17%) and pregnancy complications (8-22%) in young female workers in case of the combination with low intensity factors (75 dB "A" noise

1	2	3	4
			and 8 Hz infrasound exposure to 90 dB).
VII Zone of unclear poorly detectable effects			
	< 90 dB	2	Isolated short-time exposure is out of the health harm. Combination with noise and vibration as well as the psycho-emotional tension can amplify negative infrasound effects.
VIII Ecologically unfavorable exposure zone in case of living area exposure			
	109 dB		The significance of the population exposure is proved by the complain rate differences (disorders of day and night rest, sleeping disorders, frequent headaches). Infrasound makes not only interfering and irritating action but also induces functional disturbances.

Table 4.6 - Infrasound level (dB) effects in human organism (Nekhoroshev A.S., 1998)

Organ	Octaval band frequencies, Hz			
	2	4	8	16
Upper border of "functional rest"				
Static acoustic system	90	90	90	90
Liver	90	90	90	90
Myocardium	90	90	85	85
Upper border of "functional fatigue"				
Static acoustic system	110	110	105	105
Liver	110	110	100	100
Myocardium	115	115	110	110
Upper border of initial "functional destruction changes" *				
Static acoustic system	140	140	140	140
Liver	130	130	125	125
Myocardium	120	120	115	115

*Note. Residual infrasound induced destruction is started above initial functional changes.

Table 4.6 data reflect studies elaborated in animals (guinea pigs and white rats) exposed to infrasound within 1, 5, 10, 15, 25, 40 and 90 days (3 h daily exposure) for sound pressure levels of 90, 100, 120 and 140 dB at 2, 4, 8 and 16 Hz. Basing upon histological, histochemical and electronic microscopy data, it was found that 90 dB infrasound has not induced any change at any frequency. Static acoustic system reaction was practically similar to that for any sub-threshold irritation. Starting from 110 dB the static acoustic system has reacted by comprehensive biological changes of receptor formations, which changes depend on the exposure duration. In case of single infrasound exposure (3 hours) at any frequency, changes recorded in labyrinth receptors are in the range of "functional fatigue" i.e. if the relative sound rest is present (≤ 40 dB), the recovery occurs within 15-30 minutes. In case of the infrasound exposure within 15 days (110 dB), changes were of the similar character and were in the "functional fatigue" range. The time period required for the recovery was 6 hours of the relative sound rest at least. For longer exposure periods (40 and 90 days),

first signs of microdestruction have occurred, which signs could be revealed by electronic microscopy only.

Histochemical examinations have indicated the decrease of diffuse caryoplasma RNA with the absence of the nuclei functional pulsation. Such condition of receptor cells requires 2-2.25 days recovery at relative sound rest. Similar changes of the static acoustic system were recorded for 120 dB. 140 dB level has induces expressed pathological changes of ear labyrinth receptors, which changes have two specific features. The first feature is the release of the portion of the cytoplasm into endolymphatic area via cell apex. The second feature consists in the phenomenon of changes going out of the cell and propagating to the underlying pre-ganglia myelin nervous fibers.

Thus, 140 dB at any infrasound frequency can induce destructive irreversible changes of the static acoustic system. All these changes were more expressed for 8 Hz infrasound exposure. According to obtained data, four zones of static acoustic system reaction to the infrasound exposure were separated as follows: "functional rest" zone (A), "functional fatigue" zone (B), "initial destruction" zone (C), and "destruction" zone (D) (Figure 4.4).

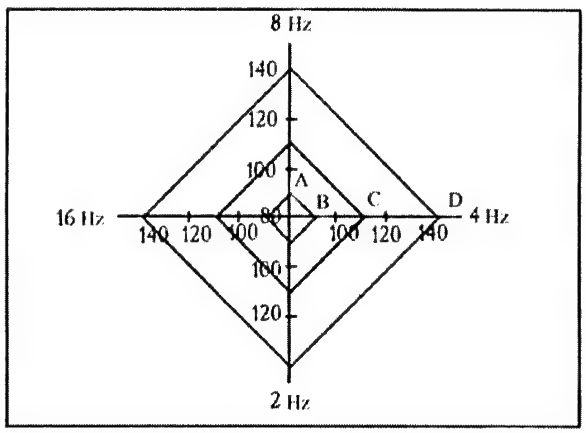


Figure 4.4 - Zones of static acoustic system reacting to the infrasound exposure
A — "functional rest"; B — "functional fatigue";
C — "initial destructive changes"; D — "destruction" (Nekhoroshev A.S., 1998)

Similarly to the static acoustic system, liver reaction to the infrasound exposure was also subdivided into 4 zones. The normal state zone ("functional rest") is limited by 90 dB. The border state zone ("functional fatigue") is limited by 100 dB (at 8 and 16 Hz) and 110 dB (at 2 and 4 Hz). The "initial destruction" zone is limited by 120 dB (at 8 and 16 Hz) and 130 dB (at 2 and 4 Hz). At 140 dB and

more the hepatocyte destruction changes would occur ("destruction" zone).

The vascular system reaction to the infrasound exposure was noted to have the cycling of capillaries and pre-capillaries reaction. This reaction had specific dependence versus rate and duration of the exposure.

For 90 dB intensity, the vascular reaction was similar to that for the noise irritation of the same parameter ("A" zone). For 90 to 100 dB at all infrasound frequencies, the moderate blood circulation stagnation in all sub-laying cerebral capillaries was recorded ("B" zone). For more intensive levels (from 100 to 110 dB), changes of the vascular wall were present including its thickening due to pericytes enlargement and mitochondria bloating ("C" zone). The observed changes can be considered as reversible because the destruction was not found. For 110 to 140 dB, the nervous tissue in near-by areas of changed vessels was found to have initial destruction signs (mitochondria ridge destruction, ribosome count decrease, and enlargement of channels of acinose endoplasmic network) ("D" zone), (Figure 4.5).

The myocardium was found to be most sensitive to the infrasound exposure. Its reaction was subdivided into three zones. The first zone was limited by 85 dB at 8 and 16 Hz and 90 dB at 2 and 4 Hz ("functional rest" zone). The "border state" zone was limited by 115 dB at 8 and 16 Hz and 120 dB at 2 and 4 Hz. The "destruction" zone is above the mentioned levels (Figure 4.6).

Thus, according to these studies and literature references noted above, 8 Hz and 16 Hz infrasound is specific to most expressed pathological changes in internal organs examined.

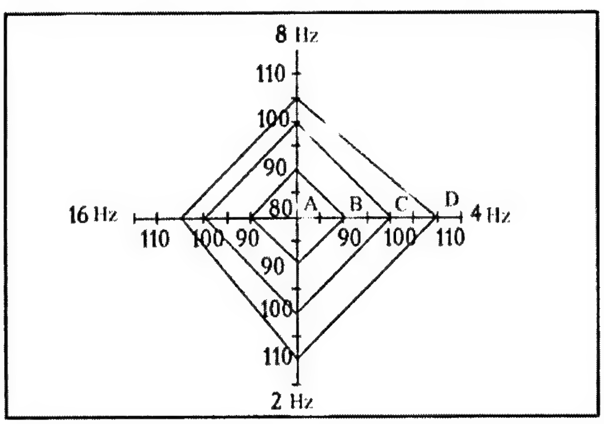


Figure 4.5 - Zones of vascular system reacting to the infrasound exposure
A — vascular reaction similar to any other irritator; B — specific vascular reaction within physiological reaction range; C — "physiological regulation" " (irreversible vascular changes); D — "accidental regulation or disease" (Nekhoroshev A.S., 1998)

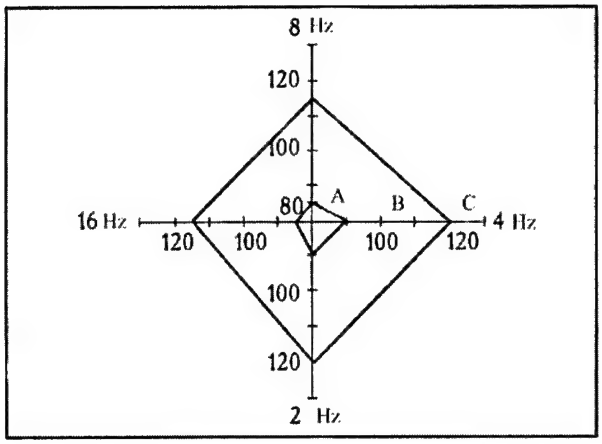


Figure 4.6 - Zones of myocardium reacting to the infrasound exposure
A — "functional rest"; B — "border-line state";
C — "destruction" (Nekhoroshev A.S., 1998)

First Russian regulation of the industrial infrasound was adopted by the State Standard (GOST) No. 12.1.003-76: "Noise. General safety requirements". Despite the industrial noise was only considered by this standard, item 3.2 of this document indicates: "... even short-time stay in the areas of active sound pressure levels above 135 dB of any octaval band is forbidden."

After the adoption of this standard, basing upon the analysis of the literature data, experimental and physiological hygienic studies, the hygienic regulation of low frequency and infrasound bands of acoustic oscillations of the air media was elaborated.

It is convenient to consider the progress of the infrasound hygienic regulation versus the accumulation of new knowledge on the health effects of the low frequency acoustic oscillations.

First national hygienic infrasound standards were developed by the Institute of Biophysics in 1979. These standards were adopted at inter-agency level due to the initiation of studies of health effects of low frequency acoustic oscillations and based upon original experimental data and physiological hygienic examinations of volunteers obtained within first 3 years of work (Table 4.7).

First official state infrasound standards were elaborated by Research Institute of Labor Hygiene and Occupational Diseases of the USSR Academy of Medical Sciences (at present, Research Institute of Labor Medicine of Russian Academy of Medical Sciences), which standards were entitled: "*Hygienic standards of the infrasound at workplaces», No. 2274-80.* (Adopted in 1980; out of force at present).

Table 4.7 - Occupational safety standards of infrasound (Institute of Biophysics, 1979)

Octaval frequency bands, Hz	0.88 - 1.4	1.4 - 2.8	2.8 - 5.6	5.6 - 11.2	11.2 - 22.4	22.4 - 45.0
Averaged geometric frequencies of octaval bands, Hz	1	2	4	8	16	31.5
Permissible levels of sound pressure, dB*	108	106	104	102	100	98

*Note: if total exposure time is less than 6 hours/working day, permissible levels will be increased according to the duration:
1-3 hours - for 6 dB;
1/4 h to 1 h - for 12 dB;
5 - 15 min - for 18 dB;
< 5 min - for 24 dB.
Even short-time exposure to > 140 dB is prohibited.

These standards are applicable not only to the occupational exposure. The standardized infrasound indices are sound pressure levels in octaval bands of averaged geometric means of 2, 4, 6, 8, 16 Hz calculated according to the following formula (dB):

$$L = 20\ lg\ P/P_0,\ dB,$$

where $P_0 = 2 \cdot 10^{-5}$ Pa.

For variable infrasound the standardized feature is the general level of the sound pressure on "linear" scale, dB "Lin".

It is acceptable to evaluate sound pressure levels in third-octaval frequency bands of 1.6, 2, 2.5, 3.15, 4, 5, 6.3, 8, 10, 12.5, 16, 20 Hz. These levels should be re-calculated to levels of octaval bands of averaged geometric frequencies given by "Methodological indications on measurements and hygienic assessment of noises at workplaces" No. 1844-78, Ministry of Health of the USSR (Table 4.8).

Table 4.8 - Sound pressure levels (dB) in octaval bands

Sound pressure levels (dB) in octaval bands at average geometric frequencies (Hz)					General sound pressure level (dB) "Lin"
2	4	8	16	31.5	
105	105	105	105	102	110 dB

Note: 31.5 Hz octave was included because it was not regulated by the State Standard, GOST 12.1.0003-76 entitled "Noise. General Safety Requirements"

In 1989 the documents on *"Sanitary standards of permissible levels of infrasound and low frequency noise in the living areas", SanPiN 4948-89* and *"Methodological indications to sanitary epidemiological surveillance services for management of the implementation of "Sanitary standards of permissible levels of infrasound and low frequency noise in the*

living areas", SanPiN 4948-89", No. 4949-89. (approved in 1989; out of force at present time).

These sanitary standards have established maximal permissible levels of the sound pressure for populated areas (i.e. were applicable in the general public).

The standardized parameters of continuous infrasound and low frequency noise are sound pressure levels, *L*, dB, at octaval bands of averaged geometric frequencies of 2, 4, 8, 16, 31.5 Hz or at 1/3 octaval bands of averaged geometric frequencies of 1.6, 2, 2.5, 3.15, 4, 5, 6.3, 8, 10, 12.5, 16, 20, 25, 31.5, 40 Hz.

Standardized parameters of intermittent infrasound and low frequency noise are energy equivalent sound pressure levels, *L*, dB, at octaval or at 1/3 octaval bands of averaged geometric frequencies listed above.

Permissible levels of the infrasound and low frequency noise pressure, dB, in the living area are given by Table 4.9.

Table 4.9 - Permissible infrasound pressure levels, dB

Frequency, Hz	2	4	8	16	31,5
Sound pressure, dB	90	90	90	90	90

Note: third octaval sound pressure levels are 85 dB.

To get the approximate assessment of the infrasound level, one can apply general sound pressure level on the "linear" scale and difference between readings of "linear" and "A" scales of the noise meters of classes 0 and 1. The permissible value of the general sound pressure level on the "linear > 2 Hz" scale is 90 dB. The grade of the infrasound expressiveness was determined by the difference of $L_{"lin"}$–$L_{"A"}$: 6-10 dB (infrasound presence sign), 11-20 dB (moderate expressiveness), 21-30 dB (expressed infrasound), and > 30 dB (significant expressiveness).

In 1997, basing upon elaborated studies and new data on infrasound effects described by the present monograph, researchers of Labor Medicine Institute, Erisman Institute, St.-Petersburg Medical Academy, and Voronezh State Medical Academy named after N.N. Burdenko have elaborated sanitary rules and standards for the infrasound exposure.

Proposed limit levels for octaval bands of 2, 4, 8 and 16 Hz were based upon the whole variety of unfavorable health changes and entitled *"Infrasound at workplaces, living and public premises and populated areas", SN 2.2.4/2.1.8.583-96.*

This regulative document is in effect at present time and establishes criteria of safety and harmlessness for human environment as well as the requirements for favorable conditions of human activities.

The present sanitary rules provide classification, hygienic regulations and requirements of measurement and assessment of the infrasound at workplaces, living areas and premises as well as requirements for the protection measures and prophylaxis of unfavorable effects and monitoring (Table 4.10).

Hygienic requirements are applicable to all new created, modernized, imported and operated machines and equipment as well as to processes specific to infrasound generation; they are presumed for usage of specialists when designing, expertizing technical documentation (Standards, Technical Terms, etc.), evaluation, certifying and distributing production in the population.

Table 4.10 - Permissible infrasound levels at workplaces, living and public premises and populated areas

No.	Premise	Sound pressure levels, dB, in octaval bands of averaged geometric frequencies, Hz				General sound pressure level dB "Lin"
		2	4	8	16	
1.	Different jobs inside industrial premises and production areas:					
	- Different physical intensity jobs	100	95	90	85	100
	- Different intellectual emotional tension jobs	95	90	85	80	95
2.	Populated area	90	85	80	75	90
3.	Living and public premises	75	70	65	60	75

The analysis of comprehensive hygienic, physiological, biochemical and morphological studies also indicates to the necessity to introduce frequency correction with the decrease of 5-6 dB/octave, alternatively to values adopted by the international standard, ISO 7196 (12 and 24 dB) which are based upon the aural effects and subjective assessment of the infrasound irritating effect.

Thus, new data on the infrasound effect mechanism have given the opportunity to propose the new principle of the safe level regulation. The proposed limit levels for octaval bands of 2, 4, 8 and 16 Hz are based upon the whole variety of unfavorable effects of the whole organism. It is suggested that the exposure to such infrasound levels within the whole working shift and occupational term (up to 40 years) would not induce specific and non-specific diseases. Basing upon physics, acoustics and physiology peculiarities of the factor and medical prophylaxis requirements, hygienic principles of the unfavorable factor exposure limitation were also developed (Table 4.11).

The obtained results have justified infrasound grouping according to its parameters and health risks as well as the harm classes and health dangers for workers and population, which was the significant addition to R.2.2.013-94 Manual entitled "Hygienic criteria for assessment of labor conditions according to indices of

harm and danger of occupational factors, intensity and difficulty of work".

Table 4.11 - Hygienic regulation principles of infrasound unfavorable exposure (Izmerov N.F. et al, 1999)

Factor peculiarities	Medical technical requirements and prophylaxis directions
1. Physics peculiarities (large wavelength and low attenuation with distance), which determines ineffectiveness of traditional protection methods applying: - distance (large distance required); - mass (poor sound isolation); - shielding (unreal sizes of shields); - time (applicable for low intensities only); - individual protection mans (low efficiency, ± 5 dB with resonance).	1. Constructive and design-acoustic solutions: - acoustics calculations of highways, tunnels, bridges etc.; - traffic flow management; - geometric principles for vulnerable territory shielding (kindergartens, schools, hospitals etc.).
2. Acoustics and physiology peculiarities: - large importance of each decibel because of narrow range of reacting from perception to the pain threshold; - specificity of aural and extra-aural effects.	2. Technological processes and equipment: - optimization of geometric and kinematics parameters; - dynamic anti-phase attenuators with resonance absorption; intensimetry techniques for diagnosis and correction of acoustic fields.
3. Peculiarities 1 + 2 in case of the MPL excess strongly increase the hygienic significance of the problem	3. Peculiarities of medical assistance of operators, car drivers etc. (occupational selection, preliminary examination, modes of work and rest etc.)

4.2 Regulation principles of the infrasound and LFAO

The Research Institute of Labor Medicine of Russian Academy of Medical sciences has formulated basic recommendations to develop and improve standards for permissible infrasound levels at workplaces, living and public premises and populated areas.

The standardization would be in accordance with the infrasound spectrum as follows: wide frequency band with continuous spectrum of more than one octave width; tonal spectrum containing aural discrete components.

The harmonic character of the ultrasound is determined by octaval frequency bands according to ≥ 10 dB excess of the level in one octane above neighboring ones. When standardizing, the temporal features of the infrasound should be taken into account (continuous and intermittent infrasound).

The continuous infrasound pressure level should be measured within the time period of its change for less than 2 times (for 6 dB), when measuring on "Linear" scale and "Slow" mode of the noise meter.

The pressure level of intermittent infrasound should be measured within the time period of its change for more than 2

times (for 6 dB), when measuring on "Linear" scale and "Slow" mode of the noise meter.

Standardized features of continuous infrasound are sound pressure levels (Lp, dB) in octaval bands of averaged geometric frequencies of 2, 4, 8 and 16 Hz determined by:

$$Lp = 10\ lg\ P^{-2}/P_0^2,\ dB$$

where P^{-2} is the quadratic mean of the sound pressure, Pa; P_0^2 is the initial value of the sound pressure in the air, $2 \cdot 10^{-5}$, Pa.

Standardized features of intermittent infrasound are energy equivalent sound pressure levels (L_{eq}) in octaval bands of averaged geometric frequencies of 2, 4, 8 and 16 Hz and equivalent integral level of the sound pressure (dB) determined by:

$$L_{eq} = 10 \lg\left(\frac{1}{T}\sum_{i=1}^{n} t_i \cdot 10^{0.1Li}\right),\ dB$$

The equivalent level can be established at the measurement time or via calculation applying the measured level and exposure duration according to the Annex.

The additional characteristics for the infrasound assessment (for instance, in case of the tonal infrasound) are sound pressure levels in 1/3 octaval bands of averaged geometric frequencies of 1.6, 2, 2.5, 3.15, 4, 5, 6.3, 8, 10, 12.5, 16 and 20 Hz. They should be recalculated to levels in octaval bands of noted averaged geometric frequencies according to "Methodological indications on measurements and hygienic assessment of workplace noises".

Table 5.5 provides permissible infrasound levels for different jobs and measurement places. For time-variable and pulsed infrasound, sound pressure levels measured on "Linear" scale should not exceed 120 dB.

For noises of aural and infrasound bands, the measurement and assessment of the corrected infrasound pressure level is the additional one to the noise assessment done according to "Sanitary standards of permissible noise levels at workplaces", No. 3223-84, GOST 12.1.003-83, "SSBT. Noise. General safety requirements" (A correction etc.), "Sanitary standards of permissible noise in living and public premises and populated areas", No. 3077-84.

In case of the occupational infrasound exposure of levels above standard, the corresponded modes of work and rest are applicable as well as other protective measures (see Table 5.6.)

In case of daily infrasound exposure (at working and free hours), the integral assessment of the exposure should be elaborated according to "Methodological indications on hygienic assessment of industrial and non-industrial noise exposure".

The measurement and hygienic assessment of he infrasound as well as the prophylaxis measures should be implemented according

to the 2.24/2.1.8-95 Manual on "Hygienic assessment of physical factors of industrial activities and environment".

Equivalent infrasound level calculation

In case of variable infrasound exposure, the equivalent level should be calculated taking into account exposure time corrections subtracted from the measured level (see Table 4.12).

Table 4.12 - Exposure time corrections to calculate the equivalent level

Exposure time									
Hours	8	7	6	5	4	3	2	1	0.5
Correction, dB	0	-0.6	-1.2	-2	-3	-4,2	-6	-9	-12

Regulative references:

1 Law of Russian Federation, "On sanitary epidemiological well-being of the population", 19.04.1991.
2 Law of Russian Federation, "On environment protection", 19.12.1991.
3 GOST 17187-71. Noise meters. General technical requirements.
4 Methodological indications on measurements and hygienic assessment of workplace noises. No. 1844-78.
5 Sanitary standards of permissible noise levels at workplaces, No. 3223-84.
6 Sanitary standards of permissible noise in living and public premises and populated areas, No. 3077-84.
7 GOST 12.1.003-83. SSBT. Noise. General safety requirements.
8 Methodological indications on hygienic assessment of industrial and non-industrial noise exposure No. 4435-87.
9 GOST 17168-89. Octaval and 1/3 octaval electric filters.
10 Methodological indications on dose assessment of industrial noises, No. 2908-82.
11 GOST 12.4.051-87. SSBT. Individual protection means for hearing organ. General technical conditions.
12 Recommendations on organization and functioning of psychological relaxation rooms, Moscow, 1988.

4.3 G frequency correction for infrasound assessment according to the ISO/DIS 7196.2 international standard

The development of criteria for infrasound exposure assessment is based upon physiological hygienic research data of industrial environment and experiments as well as the data of social hygienic character for urban population exposed to the factor of interest. The elaboration of assessment criteria gives the opportunity to

design the monitoring system including hygienic standardization, methods and means of monitoring, effects assessment and unfavorable consequences prevention.

Criteria for different character of the infrasound exposure depending upon its frequency composition are reflected by G correction applied to obtain single value assessment according to ISO/DIS 7196.2 international standard. The normal perception threshold of the infrasound is significantly higher than that for aural frequencies (~ 100 dB or 20 μPa at 10 Hz), whereas the tolerance to high levels is not increased correspondingly. Thus, the dynamic raw is less than that for aural sounds and sensitivity increase rates are significantly more delayed with the sound pressure increase. According to ISO standard, for 1 to 20 Hz frequencies, the average human perceived sound levels are about 100 dB. Very loud noise of this frequency band would be created by the weighted level of about 120 dB i.e. only 20 dB more. Weighted levels of the sound pressure, which are below ~ 90 dB will not be significant for normal average human perception.

However, it should be noted that due to the combined effect of individual differences of the perception threshold and the slope of the pre-threshold sensation, the same infrasound noise can be only more loud and stimulating for some persons, whereas others can hardly tolerate it. Moreover, the aggravating influence of the infrasound exposure can be originated from the general vibration or aural noise.

Peculiarities of G frequency correction adopted by ISO/DIS 7196.2 are the following characteristics.

G curve is determined in a such way, where the elevation to 0 dB at 10 Hz frequency, which is equal to non-weighted sound pressure level. In the range of 1 Hz to 20 Hz, the curve is close to the line of 12 dB/octave slope. Thus, each frequency is weighted according to its relative input to the perception; below 1 Hz and above 20 Hz, the curve decreases with the slope of 24 dB/octave (see Table 5.8).

Thus, the measurement device evaluating corrected infrasound level applying G correction have the amplification adjusted to show the true sound pressure level (dB) at 10 Hz versus 20 μPa. The recommended G correction accepts 10 Hz frequency as most unfavorable for human organism according to the aural sensitivity criterion. To take int account multiple nature of infrasound health effects, it is necessary to develop corresponding corrections for different criteria of the exposure assessment (including non-specific manifestations, aural sensitivity assessment applying bone conductivity index, impedance measurement data etc.).

The previous edition of ISO 7196 standard has provided two corrections for the infrasound assessment: specific (G1) and non-specific (G2) criteria.

Table 4.13 - G frequency correction according to ISO/DIS 7196.2 standard

Frequency (Hz)	Relative characteristic, G dB)
0.5	-64.5
0.63	-56.5
0.8	-49.5
1.00	-43
1.25	-37.5
1.6	-32.5
2.0	-28.5
2.5	-24
3.15	-20
4.0	-16
5.0	-12
6.3	-8
8.0	-4
10.0	0
12.5	4
16.0	8
20.0	9
25	4
31.5	-4
40	-12
50	-20
63	-28
80	-36
100	-44
125	-52
160	-60
200	-68
250	-76
315	-84

4.4 Infrasound monitoring in industry and environment

The infrasound monitoring should be provided by equipment, monitoring techniques and organizations responsible for monitoring implementation according the especially designed programs.

Acoustic parameter measurement means

Depending upon the complexity of noise investigated and investigation purposes, the acoustic measurement practice applies portable devices (noise meters) or the equipment complex composed of measurement tract, magnetic recorder and analyzer.

Noise meters are subdivided into four accuracy classes as follows: reference measurement devices (class 0); accurate laboratory and field measurement devices (class 1); routine accuracy measurement devices (class 2); approximate measurement devices (class 3). The routine accuracy presumes measurement error below ±1 dB, with 68% confidence interval. Frequency range is determined by the microphone and should be 20 Hz-12.5 kHz (class 1), 20 Hz-8 kHz (class 2), 31.5 Hz-8 kHz (class 3).

Noise meter contains frequency correction circuits for scales "A", "B", "C", "D" and "Lin"; averaging modes correspond to time characteristics of "Fast", "Slow", "Impulse", and "Peak" and give the opportunity to measure sound level (dB"A") and sound pressure level (dB). "Fast" and "Slow" averaging modes are used to measure stationary noise processes and "Impulse" mode is used for non-stationary processes containing pulses. If the "Slow" mode measurement demonstrates the sound pressure level change for less than 5 dB, such noise is named as continuous; otherwise it is intermittent.

To measure equivalent sound level integrating noise meters are available. Accuracy classes of integrating noise meters are that for routine noise meters. The noise dose is measured by dosimeter, which is the integrating noise meter.

The noise measurement complex is usually composed of microphone, preamplifier, microphone power supply, recorder, frequency analyzer, paper recorder and reference sound source. Recently, the computer based modules are used for recording and processing of acoustic measurement results.

The list of commercially available equipment is rather long. At the period of Mutual Economy Aid Council (SEV) manufacturers of niose measurement equipment were Robotron-Messelektronik (East Germany) and Vibropribor (USSR, Taganrog). Other firms include Metravib (France), Ono Sokki (Japan), Endevco (USA), Bruel and Kjaer (Denmark). This list can be prolonged because worldwide noise measurement equipment needs are very high and each developed country has its own manufacturer.

The most comprehensive assortment of acoustic equipment is manufactured by Bruel and Kjaer (Denmark), which company elaborates original research to develop new techniques and measurement equipment together with their quality assurance according to international practice. The survey of this company equipment would provide most complete and modern view of acoustic measurement equipment.

At present time, the infrasound measurements in Russia are elaborated by classes 0 and 1 noise meters according to GOST 17187, "Noise meters. General technical requirements" with the amplifier frequency band from 2 Hz and octaval (or 1/3 octaval) band filters according to GOST 17168, "octaval and 1/3 octaval electric filters" as well as auxiliary devices (tape recorders, paper recorders etc.). The equipment recommended for infrasound measurements is enlisted by Table 4.14. Noise meter microphones should have the lower border frequency < 20 Hz; microphones of series of 4144, 4145, (4146) etc. manufactured by Bruel and Kjaer (Denmark) are recommended, which microphones have frequency characteristic from 3-4 Hz giving the opportunity to apply them from 2 Hz with correspondent correction.

Auxiliary devices (paper recorders) should be used with the frequency characteristic from 2 Hz: for instance, series 2317, 2305, 2306 or 2307 (Bruel and Kjaer, Denmark), 2013 (RFT, Germany) can be used to record spectra to the paper band as well as to record levels on "Linear" scale, when examining intermittent infrasound. Averaging time constants can be arbitrary selected to get "Slow" or "Fast" characteristics as well as large time constants to eliminate level fluctuations.

Tape recorders with frequency characteristic of ≥ 2 Hz, for instance, HO-36 or 7003 (Bruel and Kjaer, Denmark), are applicable to record inrasound for consequent spectral analysis and level distribution assessment. These tape recorders give the opportunity to make the frequency transformation, for instance, with 1:10 ratio, which gives the opportunity to analyze infrasound at sound frequency spectrometers to save time, because the frequency transformation corresponds to the time compression.

The level analyzer like series 4426 (Bruel and Kjaer, Denmark) is applicable to get the still distribution of levels or equivalent level within the observation period.

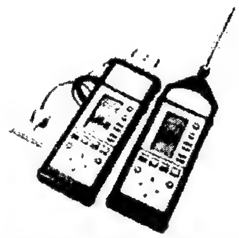
Table 4.14 - Equipment recommended for infrasound measurements

Noise meters, measurement devices	Frequency analyzer	Frequency correction	Measurement range	
			dB	Hz
VShV 003 M-2, Vibropribor, Taganrog, Russia	Built-in filter	A, C, Lin	30–140	1–16 Hz octave
ShVK-1, Vibropribor, Taganrog, Russia	–	–	30–140	2–16 Hz octave
2260 Bruel and Kjaer, Denmark		Difference between A and C	24–140	2–16 Hz
2231 Bruel and Kjaer, Denmark	1627 filter	A, C, Lin, wide band 61 and 62	24–130	
Real time frequency analyzers 2143, 2144		A, C, Lin, arbitrary corrections		0.5 Hz–16 kHz octave
2631 system with 7003 tape recorder Bruel and Kjaer, Denmark	2131 analyzer		60–140	0,25–16 Hz octave (1/3 octave of 0.2–20 Hz)
2204 or 2209 Bruel and Kjaer, Denmark	1614 filter	A, C, Lin	12–148	4, 8 and 16 Hz octave (1/3 octave of 2–20)
Approximate infrasound spectral assessment equipment				
00017 RFT (Germany)	OF-201 Built-in filter		19–140	8 and 16 Hz octave

At present time in Russia, "Oktava" portable devices to measure noise, vibration, infrasound and ultrasound are manufactured (see picture below). Technical information of this device is available in web sites: www.eco-intech.com/octava.html and www.octava.ru.

Октава-101

Приборы для измерения шума, вибрации, инфразвука



Октава-101А Шумомер - анализатор спектров

Октава-101В Виброметр - общей и локальной вибрации

Октава-101С Измеритель ультразвука

Технические характеристики	
Общие	
Дисплей	ЖКД, 128x64 точек, с регулированием подсветки и контрастности
Последовательный интерфейс	RS-232
Память	энергонезависимая 0,5 Мб (расширение до 16 Мб)
Питание	4 аккумулятора 1,2 В (не менее 7 часов непрерыаной работы); от сети 220 В через блок питания - зарядное устройство
Вес	около 700 г с предусилителем
Октава-101А	
Режимы измерений	Звук, Инфразвук
Класс точности	1
Диапазон измерений	22 -145 дБА (СКЗ) (с микрофоном ВМК-205)
Частотная коррекция	A, C, Лин
Частотный диапазон	1,4 Гц - 22,6 кГц
Частотные фильтры	1/3-октавные фильтры 1,6 Гц - 16 кГц 1/1-октавные фильтры 2 Гц - 16 кГц (класс 1 по МЭК 1260)
Измеряемые параметры, режим "Звук"	Уровни звука L, Lмакс, Lмин (S, F, I; с коррекцией A, C, Лин), Lэкв, Lпик, уровни звукового давления (УЗД) в 1/1 или 1/3-октавных полосах частот
Измеряемые параметры, режим "Инфразвук"	УЗД в 1/1 и 1/3-октавных полосах частот, и уровни звука с коррекцией А и Лин: L, Lмакс, Lмин (усреднение 1 с, 10 с), Lэкв
Микрофон	конденсаторный, 1/2-дюйма, 45 мВ/Па
Удовлетворяемые стандарты	МЭК 651-1993, 804-1993, 1260, ГОСТ 17187

Infrasound measurement elaboration

Permanent workplace measurements (at control shields, inside cabins and control rooms, etc.) or measurements in the production areas should be elaborated at the time of routine working of the equipment. Measurement points should be placed at ≤ 20 m distances (for production premises) and at ≤ 3 m (control rooms). Inside transportation machines, living and public premises the measurements should be elaborated with open and closed windows.

The microphone should be positioned at 1.5 m height from the floor and ≥ 0.5 m from the person elaborating the measurement.

When assessing infrasound exposure in the personnel, the microphone should be placed at 15 cm from the ear.

If the noise meter does not have the G frequency correction, the measurement should be started from the evaluation of difference between "Linear" scale reading and "A" scale reading with "Slow" mode applied. If the difference, $L_{\text{"Lin"}}-L_{\text{"A"}}$ is less than 5 dB, the infrasound is practically absent and spectra analysis is not necessary. To determine the infrasound character, the average value for "Linear" or "G" scale at "Slow" mode and limits of this value variation should be recorded.

In case of continuous infrasound, sound pressure levels (dB, G) or sound pressure levels in octaval bands of the infrasound rage should be measured with reference to maximal measured value with "Slow" mode or the tape recording should be done; for intermittent infrasound (repeated peaks or pulses), the correspondent equivalent levels should be determined. In case of intermittent infrasound (repeated peaks or pulses) measurements should be done at "Fast" mode and maximum value should be recorded.

When assessing octaval 9or 1/3 octaval) sound pressure levels, the measurement time should correspond to periods given by Table 4.15. The measurement time should be rather long to get confident result reflecting measured infrasound characteristics. The integration time (time constant) should be 10 s. When examining the infrasound with maximal levels in the upper part of the frequency raw of 1-20 Hz, the minimal integration time can be 1 s.

When assessing infrasound equivalent time using tape record analysis, the level counting should be done at 5-6 s intervals within 30 minutes; the followed calculation should be elaborated according to GOST 20445-75, "Industrial buildings and premises. Workplace noise measurement method". In case of the slow change of the level, its magnitudes are recorded simultaneously with time counting and equivalent level calculation should be done applying second technique provided by GOST 20445-75, "Industrial buildings and premises. Workplace noise measurement method".

Table 4.15 - Minimal and recommended measurement time for infrasound frequency analysis

Measurement time, s	Average geometric frequencies of octaval bands, Hz				
	1	2	4	8	16
Minimal	60	30	15	8	4
Recommended	450	300	150	80	40

Note: Minimal and recommended measurement time is corresponded by level statistical errors of ±3 dB and ±1 dB with confident probability.

4.5 LFAO protection means

Because of the comprehensive spatial temporal structure of low frequency acoustic oscillations, the protective means development have to be based upon physical regularities of their propagation. Large wavelengths specific to these oscillations determine their expressed diffraction ability and significant magnitudes of oscillation movements give the opportunity to affect biological objects at long distances from the source.

Therefore, the design of different shields even of large linear sizes does not provide sufficient decrease of LFAO intensity. For instance, the iron concrete shield placed at Paris-Lion highway was found to give the sound attenuation far below the projected one. That is why the project of such shielding constructions at other French highways was not realized (Novogrudsky E.E. et al, 1990). The analysis of such circumstances has concluded to the necessity of the intensity decrease "in the source" applying special attenuating appliances of small linear sizes to re-distribute the spectral composition of acoustic signals to higher frequency range (Gavreau V., 1968) as well as the application of interference absorbers. However, such techniques are often inapplicable and individual protection means are the only way.

In 1970th - 1980th different laboratories have developed and tested different protective means of aural system and head against LFAO: anti-noises, headphones, pressure helmets etc. The detailed survey and analysis of such protective means for individual is provided by L. Pimonow (1976) and N.I. Karpova and E.N. Malyshev (1981) as well. The attenuation ability of such means at high frequencies is 8-47 dB and it is significantly lower at low frequencies (Suvorov G.A., 1983).

However, the systemic body reaction to this factor is performed by mechanical receptors of skin, muscles and internal organs together with aural receptors. The lower intensity of acoustic stimulation is present, the higher perception importance is attributed to high-sensitive mechanical sensory systems. Basing upon this finding, it is convenient to consider protecting means other than aural and air means, when developing protection and prophylaxis against LFAO. This very way of acoustic damage prophylaxis was noted by V.I. Voyacheck (1941). This author has proposed the technique of "armoring" skin applying protective suits made of fabrics of high acoustic impedance able to effectively reflect low frequency acoustic oscillations. The necessity of protection of such large receptor area like skin was later mentioned by other researchers (Chedd G., 1975). The increase of stiffness of biological objects clothed in such protective suits is able to change frequency of separate absorption of the acoustic oscillation energy. Such protection prevents the low frequency oscillation exposure of

muscular and visceral sensors. Therefore, the possibility of the reception of low intensive LFAO in all basic mechanical sensorial has to underline hygienic studies to develop protective means of new principles.

Industrial LFAO are usually combined to aural noises and vibration. Such combined exposure of additive character significantly complicates the LFAO separation and control in industry and transportation. Thus, classic ways f the noise control are low effective (Alexeev S.V., Usenko N.A., 1989).

The analysis of prepositions named above gives the opportunity to separate following basic directions of the improvement of ecological safety of low frequency acoustic exposure:

- LFAO attenuation "in the source" and elimination of originating causes;
- LFAO isolation;
- LFAO absorption;
- Individual protection development;
- LFAO medical prophylaxis.

To decrease LFAO intensity "in the source", the interference technique can be successfully applied, which technique is based upon the application of mechanical oscillation anti-emitters as well as protectors and absorbers. Moreover, techniques of acoustic oscillation reflection back to the source as well as the mechanical energy absorption on the propagation way (silencing and sound absorbing materials with relief surface) can be effective.

The LFAO control involves protective means classified in the following Table:

MEANS FOR PROTECTION AGAINST LOW FREQUENCY ACOUSTIC OSCILLATIONS	
INDIVIDUAL	COLLECTIVE
Headphones	Attenuation in the source
Ear bushes	Sound isolating chambers
Noise silencing helmets	Sound absorbing shields with relief surface
Electronic protectors	Sound absorbing walls
Sound suits	Source dampers

At present time, the approaches are determined and adequate simulation techniques are developed for assessment of LFAO exposure in the human organism, which provides the ability of hygienic standardization and development of individual and collective protection means.

The dynamics of maximum permissible levels of the infrasound and low frequency acoustic oscillations at the period of 1973-2000 is summarized by Table 4.16 and Picture 4.7.

Table 4.16 - MPLs dynamics for LFAO and infrasound in 1973-2000

1973	MPLs recommended by Paris International colloquium (CNRS)				
Frequency, Hz	1	2	4	8	16
Sound pressure levels, dB	135	130	125	120	116

1973	MPLs recommended by D. Johnson				
Frequency, Hz	1	2	4	8	16
Sound pressure levels, dB	139.6	135	130	125	120

1974	MPLs which excess can damage the hearing (C.W. Nixon)			
Exposure duration	Frequency, Hz			
	1	5	10	20
8 minutes	150	150	145	140
1 hour	145	138	135	132
8 hours	136	129	126	123
24 hours	131	124	121	118

1975	Short-time (< 8 minutes) exposure MPLs (von H.E. Gierke et al)		
Frequency, Hz	1 - 7	8 - 11	12 - 20
Sound pressure levels, dB	150	145	140

1979	Occupational exposure MPLs (Institute of Biophysics)					
Exposure duration	Average geometric frequencies of octaval bands, Hz					
	1	2	4	8	16	31.5
6 hours	108	106	104	102	100	98
From 1 hour to 3 hours	114	112	110	108	106	104
From 15 minutes to 1 hour	120	118	116	114	112	110
From 5 to 15 minutes	126	124	122	120	118	116
Less than 5 minutes	132	130	128	126	124	122
Note: Even short-time exposure to sound pressure level of more than 140 dB is prohibited						

1980	"Hygienic standards of infrasound at workplaces", No. 2274-80 (Research Institute of Labor Hygiene and Occupational diseases of the USSR Academy of Medical Sciences et al)				
Average geometric frequencies, Hz	2	4	8	16	31.5	Integral SPL, dB "Lin"
Sound pressure levels, dB	105	105	105	105	102	110

1981	MPLs for low frequency and infrasound noise at workplaces (N.I. Karpova, E.N. Malyshev)							
Average geometric frequencies, Hz	0.5	1	2	4	8	16	31.5	63
Sound pressure levels, dB	120	117	114	111	108	105	102	99

1989	"Sanitary standards of infrasound and low frequency noise at populated areas" SanPiN 4948-89 (Research Institute of Labor Hygiene and Occupational diseases of the USSR Academy of Medical Sciences et al)				
Average geometric frequencies, Hz	2	4	8	16	31.5
Maximum permissible sound pressure levels, dB	90	90	90	90	90

1996	Infrasound at workplaces, living and public premises and populated areas" (Labor Medicine Research Institute of Russian Academy of medical Sciences et al)				
Type of premises	SPL, dB, in octaval bands with average geometric frequencies, Hz				Integral SPL, dB, "Lin"
	2	4	8	16	
Jobs of different intensity inside industrial premises and at the industrial territory:					
- different intensity jobs	100	95	90	85	100
- intellectual and emotional jobs	95	90	85	80	95
Populated areas	90	85	80	75	90
Living and public premises	75	70	65	60	75

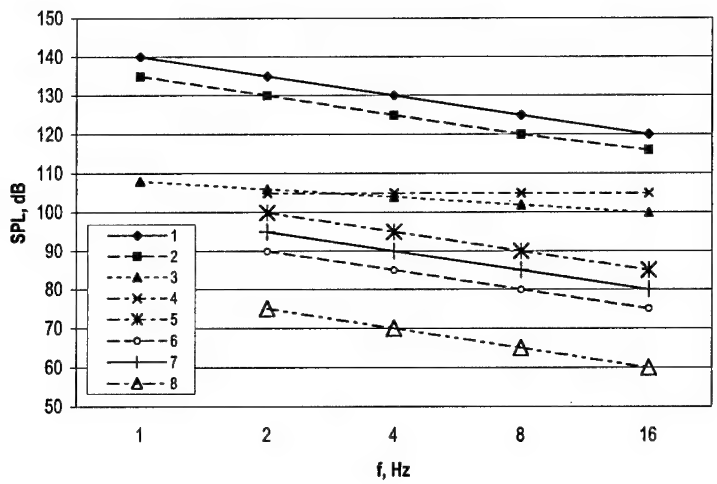


Figure 4.7 - MPLs dynamics for LFAO and infrasound in 1973-2000

1 - MPLs recommended by D. Johnson and C. Nixon (1973);
2 - MPLs recommended by Paris International colloquium (CNRS) (1973);
3 - MPLs recommended by Institute of Biophysics (1979);
4 - MPLs recommended by Research Institute of Labor Hygiene and Occupational diseases of the USSR Academy of Medical Sciences et al (1980);
5, 6, 7 and 8 - modern MPLs recommended by Labor Medicine Research Institute of Russian Academy of medical Sciences et al (1996); Jobs of different intensity inside industrial premises and at the industrial territory (5), intellectual and emotional jobs (6), Populated areas (7), Living and public premises (8).

Chapter 5 CLINICAL MONITORING OF HEALTH STATUS IN PEOPLE EXPOSED TO THE OCCUPATIONAL LOW FREQUENCY ACOUSTIC OSCILLATIONS

First experimental studies of health effects of LFAO were initiated in the Institute of Biophysics (1976–1977) and accompanied by physiological hygienic and clinical examinations of volunteers; these studies were directed to determine and analyze physiological and pathophysiological reactions of human organism.

The volunteers have been clinically examined at clinic of the Institute of Biophysics before tests. These 5–6 day examinations have included clinical and laboratory tests and examinations of internist, otolaryngologist, surgeon, ophthalmologist and neurologist. Basing upon the medical expert conclusion, the volunteer was permitted or discharged for tests. Each volunteer involved in the experiment has been accompanied by so-called medical testing passport containing all examination results and health status conclusion.

Later on, this medical passport was used to record all conditions of physiological hygienic studies including SPL values, time and place of experiment and so on as well as health state changes. After each experimental series (of ~ 7-10 day period), all volunteers were repeatedly examined in clinic within 2-3 days. These rules were kept within the whole study period, so the clinical database has been created for different exposure conditions.

All staff members employed to work with this new physical factor have been also medically examined on annual basis.

More than 25 years of studies have provided clinical database for all staff members and volunteers involved in experiments on health effects of low frequency acoustic oscillations, which has given the opportunity to create the system of clinical monitoring for persons of occupations related to LFAO exposure.

Having in mind that database is very vast, the present chapter of the monograph uses data for one year only, which data seem to be characteristic to understand the picture of clinical studies elaborated and changes possibly induced by the occupational contact with LFAO.

1998 clinical examination program

In 1998, the principles of patient examination were similar to that used before. The examination was elaborated according to standard program. Despite routine clinical internist examinations

and clinical neurological examination, the program has included following tests:

- Clinical blood count;
- Urine analysis (general);
- Extended biochemical blood count with some indices able to evaluate functional status of different body systems (glucose, cholesterol, bilirubun, triglycerides) and some organs (AST, ALT, GT, alkaline phosphatase, urea, creatinine, urea acid);
- Examination of bronchi pulmonary system applying computed diagnosis of lung function and chest X-ray imaging;
- ECG to evaluate cardiovascular system state;
- Cerebral hemodynamics (REG);
- audiometry;
- Ophthalmology examination;
- EEG examination;
- Extended psychophysiological examination (computed test systems).

If necessary, ultrasound sonography, X-ray imaging of skull, spinal cord, and computed tomography were applied.

Examined contingent features

In 1998, 78 persons have been examined in clinic of the Institute of Biophysics. Tables 5.1, 5.2 and 5.3 provide data on total number of patients, age distribution, duration of the occupational activities, and distribution of age groups versus occupation duration.

Table 5.1 - Age, sex (M/F) and number of persons examined in 1998

Age group, years									
< 39		40 - 49		50 - 59		≥60		Total	
M	F	M	F	M	F	M	F	M	F
9	1	24	2	25	3	14	-	72	6

Table 5.2 - Occupation duration

Occupation duration, years					
absent	1 - 4	5 - 9	10 - 14	≥15	Total
13	16	22	6	21	78

Table 5.3 - Distribution of age groups versus occupational activity period

Occupational activity period	Absent		< 5 years		5-9 years		10-14 years		15 years and more		Total (on age groups)	
Age group	abs.	%	abs.	%	abs.	%	abs.	%	abs.	%	abs.	%
Group I (< 39)	1	10.00	6	60.00	2	20.00	1	10.00	-	-	10	12.82
Group II (40-49)	5	19.23	3	11.54	6	23.08	4	15.38	8	30.77	26	33.33
Group III (50-59)	6	21.43	6	21.43	9	32.14	-	-	7	25.00	28	35.90
Group IV (> 60)	1	7.14	1	7.14	5	35.71	1	7.14	6	42.86	14	17.95
Total (on occupation)	13	16.67	16	20.51	22	28.21	6	7.69	21	26.92	78	100.0

The data indicate that males of 40 to 59 years ages are dominated (age groups II and III comprise 69.2%). Persons of occupation duration of > 5 years comprise 62.8 % of all persons examined. Age group I had the majority of people (60%) with occupational contact within less than 5 years. Half of people of age group IV had occupation duration of > 10 years.

Clinical laboratory results

ECG cardiovascular system status

Standard ECG leads were applied. Examination results are provided by Tables 5.4 and 5.5.

Table 5.4 - ECG results in different age groups

ECG changes	Age, years							
	< 39 n = 10		40 - 49 n = 26		50 - 59 n = 28		> 60 n = 14	
	abs.	%	abs.	%	abs.	%	abs.	%
Left ventricle hypertrophy	3	30.00	2	7.69	6	21.43	4	28.57
Conductivity disturbance	1	10.00	4	15.38	6	21.43	4	28.57
Rhythm disturbance	0	-	0	-	0	-	0	-
Diffused myocardial changes	4	40.00	7	26.92	14	50.00	10	71.43

Table 5.5 - ECG results in different occupation duration groups

Diagnosis	Occupation duration, years									
	absent n=13		< 5 n = 16		5 - 9 n = 22		10 - 14 n = 6		> 15 n = 21	
	abs.	%	abs.	%	abs.	%	abs.	%	abs.	%
Left ventricle hypertrophy	4	30.77	5	31.25	1	4.55	4	66.67	1	4.76
Conductivity disturbance	0	0.00	5	31.25	3	13.64	2	33.33	5	23.81
Rhythm disturbance	0	-	0	-	0	-	0	-	0	-
Diffused myocardial changes	8	61.54	10	62.50	4	18.18	4	66.67	2	9.52

The provided Tables indicate to sinusoidal rhythm recorded in all age groups. Left ventricle hypertrophy and myocardial diffuse

changes were found in all age groups but > 50 year age group was specific to higher incidence. The age dependent increase of cardiac conductivity disturbance incidence was found. The left ventricle hypertrophy had the elevation trend with age and occupation duration.

Basing upon ECG data and clinical observations, the cardiovascular pathology was found including arterial hypertension, ischemic heart disease, and cardiomyopathy. The incidence of this pathology versus age and occupation duration is provided by Tables 5.6 and 5.7.

Table 5.6 - Cardiovascular pathology incidence in different age groups

Diagnosis	Age, years							
	< 39 n = 10		40 - 49 n = 26		50 - 59 n = 28		> 60 n = 14	
	abs.	%	abs.	%	abs.	%	abs.	%
Arterial hypertension	4	40.00	9	34.62	11	39.29	9	64.29
Ischemic disease	-	-	-	-	2	7.14	2	14.29
Myocardiopathy	-	-	-	-	1	3.57	-	-

Table 5.7 - Cardiovascular pathology incidence in different occupation duration groups

Diagnosis	Occupation duration, years									
	absent n=13		< 5 n = 16		5 - 9 n = 22		10 - 14 n = 6		> 15 n = 21	
	abs.	%	abs	%	abs.	%	abs.	%	abs.	%
Arterial hypertension	5	38.46	5	31.25	13	59.09	3	50.00	9	42.86
Ischemic disease	2	15.38	-	-	2	9.09	-	-	-	-
Myocardiopathy	-	-	-	-	1	4.55	-	-	-	-

These data indicate that persons of > 40 year ages and > 5 year occupation had the arterial hypertension dominance.

Clinical examination results: nervous and locomotor systems

The conclusion on the status of nervous system and locomotor apparatus (LA) has been based upon clinical neurological examination, eye bottom state, REG and EEG results. Tables 5.8 and 5.9 provide basic pathological changes of nervous and locomotor systems versus age and occupation duration.

Table 5.8 – Neurological and locomotorium pathology incidence in different age groups

Diagnosis	Age, years							
	< 39 n = 10		40 - 49 n = 26		50 - 59 n = 28		> 60 n = 14	
	abs.	%	abs.	%	abs.	%	abs.	%
Focal or microfocal neurological dysfunction	1	10.00	2	7.69	1	3.57	1	7.14
Dyscirculatory encephalopathy	2	20.00	7	26.92	14	50.00	9	64.29
Including that with focal dysfunction	1	10.00	3	11.54	6	21.43	7	50.00
Neuro-circulatory dystonia	1	10.00	1	3.85	-	-	1	7.14
Vegetative vascular dystonia	1	10.00	1	3.85	-	-	-	-
Vertebral artery syndrome	-	-	1	3.85	-	-	-	-
Arthralgia syndrome	1	10.00	-	-	3	10.71	3	21.43
Ostealgia syndrome	-	-	-	-			1	7.14
Myalgia syndrome	3	30.00	6	23.08	4	14.29	4	28.57
Radicular syndrome	1	10.00	-	-	-	-	-	-
Reflex tonic syndrome	5	50.00	11	42.31	16	57.14	10	71.43
Ostechondrosis of one vertebral part	3	30.00	4	15.38	5	17.86	1	7.14
Ostechondrosis of several vertebral parts	-	-	9	34.62	14	50.00	10	71.43
Including that at manifestation phase	-	-	2	7.69	3	10.71	1	7.14
Vertebral development disorders	1	10.00	-	-	-	-	1	7.14
Systemic diseases of the connective tissues (including that in anamnesis)	1	10.00	-	-	-	-	-	-
Metabolism and trophic diseases	-	-	-	-	2	7.14	1	7.14
Locomotorium trauma consequences	1	10.00	-	-	-	-	1	7.14
Including that with pain syndrome	1	10.00	-	-	-	-	-	-

Table 5.9 – Neurological and locomotorium pathology incidence in different occupation duration groups

Diagnosis	Occupation duration, years									
	absent n=13		< 5 n = 16		5 - 9 n = 22		10 - 14 n = 6		> 15 n = 21	
	abs.	%	abs.	%	abs.	%	abs.	%	abs.	%
Focal or microfocal neurological dysfunction	1	7.69	11	68.75	1	4.55	-	-	1	4.76
Dyscirculatory encephalopathy	5	38.46	6	37.50	9	40.91	2	33.33	10	47.62
Including that with focal dysfunction	1	7.69	5	31.25	9	40.91	-	-	2	9.52
Neuro-circulatory dystonia	-	-	2	12.50	-	-	-	-	1	4.76
Vegetative vascular dystonia	1	7.69	-	-	-	-	-	-	1	4.76
Vertebral artery syndrome	-	-	1	6.25	-	-	-	-	-	-
Arthralgia syndrome	2	15.38	3	18.75	1	4.55	-	-	1	4.76
Ostealgia syndrome	-	-	1	6.25	-	-	-	-	0	-
Myalgia syndrome	4	30.77	6	37.50	6	27.27	-	-	1	4.76
Radicular syndrome	-	-	1	6.25	-	-	-	-	0	
Reflex tonic syndrome	6	46.15	8	50.00	13	59.09	2	33.33	13	61.90
Ostechondrosis of one vertebral part	-	-	2	12.50	5	22.73	-	-	4	19.05
Ostechondrosis of several vertebral parts	6	46.15	8	50.00	9	40.91	2	33.33	12	57.14
Including that at manifestation phase	3	23.08	1	6.25	1	4.55	-	-	1	4.76
Vertebral development disorders	-	-	1	6.25	1	4.55	-	-	-	-
Systemic diseases of the connective tissues (including that in anamnesis)	-	-	1	6.25	-	-	-	-	-	-
Metabolism and trophic diseases	2	15.38	1	6.25	-	-	-	-	-	-
Locomotorium trauma consequences	-	-	1	6.25	1	4.55	-	-	-	-
Including that with pain syndrome	-	-	1	6.25	-	-	-	-	-	-

The majority of examined patients had not complains at admission. The detailed questioning has revealed complains to periodic headache attacks of different kind, intensity and localization; back pain attacks were usually related to elevated or inadequate physical or intellectual load. The percentage of persons revealed to have diagnosis of osteochondrosis (at or outside of manifestation phase) and dyscirculatory encephalopathy has the regular age dependence. Vascular reactions within the framework of neurocirculatory and vegetative vascular dystonia were alternatively noted in < 50 year age group.

When evaluating the dependence of neurological disease incidence (dyscirculatory encephalopathy, pain syndromes, osteochondrosis) versus occupation duration, the increase of cerebral dyscirculatory disturbances was found.

Nervous system dysfunctions (VVD, NCD) were basically noted in < 9 year employees. This finding can be explained by lower average age in this group of people.

Breath system status

When analyzing breath organ state, the following indices were accounted: complains, clinical picture of bronchi and lungs, chest X-ray imaging data. Besides, the functional state of bronchi pulmonary system was assessed. Applying 3T-3000 spiroanalyzer (Japan), the lung volume was assessed in absolute units and percents of norm; maximal lung ventilation and forced lung volume ("flow-volume" curve) were also examined. Tiffno-Votchel test and functional state of large, middle and fine bronchi was assessed.

These examinations have concluded to the state of both the lung tissue itself and bronchi of all sizes. X-ray imaging results, lung function examinations and clinical diagnosis are provided by Tables 5.10-5.13.

Table 5.10 - Chest X-ray examination results in different age groups

Diagnosis	Age, years							
	< 39 n = 10		40 - 49 n = 26		50 - 59 n = 28		> 60 n = 14	
	abs.	%	abs.	%	abs.	%	abs.	%
Pathological changes	4	40.00	15	57.69	17	60.71	11	78.57
Pulmonary picture amplification	3	30.00	14	53.85	16	57.14	10	71.43
Deformation	1	10.00	1	3.85	6	21.43	4	28.57
Pneumosclerosis	-	-	1	3.85	5	17.86	3	21.43
Solderings	-	-	1	3.85	1	3.57	2	14.29
Focal shadows	1	10.00	2	7.69	3	10.71	4	28.57

Table 5.11 - Chest X-ray examination results in different occupation duration groups

Diagnosis	Occupation duration, years									
	absent n=13		< 5 n = 16		5 - 9 n = 22		10 - 14 n = 6		> 15 n = 21	
	abs.	%	abs.	%	abs.	%	abs.	%	abs.	%
Pathological changes	8	61.54	11	68.75	14	63.64	3	50.00	11	52.38
Pulmonary picture amplification	8	61.54	10	62.50	12	54.55	3	50.00	10	47.62
Deformation	3	23.08	1	6.25	6	27.27	-	-	2	9.52
Pneumosclerosis	3	23.08	-	-	3	13.64	-	-	3	14.29
Solderings	1	7.69	1	6.25	-	-	-	-	2	9.52
Focal shadows	3	23.08	2	12.50	4	18.18	-	-	1	4.76

Table 5.12 - Lung function examination results in different age groups

Diagnosis	Age, years							
	< 39 n = 10		40 - 49 n = 26		50 - 59 n = 28		> 60 n = 14	
	abs.	%	abs.	%	abs.	%	abs.	%
Lung function disorder	4	40.00	19	73.08	19	67.86	7	50.00
Obstruction	2	20.00	12	46.15	11	39.29	5	35.71
Restriction	1	10.00	4	15.38	7	25.00	2	14.29
Mixed changes	1	10.00	3	11.54	1	3.57	-	-

Table 5.13 - Lung function examination results in different occupation duration groups

Diagnosis	Occupation duration, years									
	absent n=13		< 5 n = 16		5 - 9 n = 22		10 - 14 n = 6		> 15 n = 21	
	abs.	%	abs.	%	abs.	%	abs.	%	abs.	%
Lung function disorder	8	61.54	9	56.25	15	68.18	4	66.67	13	61.90
Obstruction	6	46.15	6	37.50	8	36.36	3	50.00	7	33.33
Restriction	-	-	1	6.25	7	31.82	-	-	6	28.57
Mixed changes	2	15.38	2	12.50	-	-	1	16.67	-	-

Tables indicate that all age groups were found to have changes in X-ray images of lungs. The relative rate of these changes was regularly increased with age. The clear dependence versus occupation duration was not found.

The lung function examination (3T-3000 spiroanalyzer) has indicated that more than the half of examinees (62.8%) had lung ventilation function within the normal range. In all age groups, obstruction and restriction of lung function were noted. Inasmuch, obstructions were more frequent in the second age group against restrictions found more frequently in group III. Small number of mixed disturbances was noted in groups I, II and III (i.e. in < 60 year age persons).

Some increase of lung function disturbance incidence was noted in persons of > 5 year occupation. Basing upon clinical laboratory

tests, a number of examinees were found to have followed pulmonary pathologies (see Tables 5.14, 5.15).

Table 5.14 and 5.15 demonstrate that the elevation trend of chronic bronchitis is present with the increase of age and occupation duration.

Table 5.14 - Bronchi pulmonary pathology incidence in different age groups

Diagnosis	Age, years							
	< 39 n = 10		40 - 49 n = 26		50 - 59 n = 28		> 60 n = 14	
	abs.	%	abs.	%	abs.	%	abs.	%
Pulmonary insufficiency	-	-	2	7.69	1	3.57	-	-
Pneumosclerosis	-	-	1	3.85	-	-	1	7.14
Chronic bronchitis	-	-	5	19.23	4	14.29	3	21.43
Lung emphysema	-	-	-	-	1	3.57	1	7.14
Bronchial asthma	-	-	-	-	1	3.57	-	-

Table 5.15 - Bronchi pulmonary pathology incidence in different occupation duration groups

Diagnosis	Occupation duration, years									
	absent n=13		< 5 n = 16		5 - 9 n = 22		10 - 14 n = 6		> 15 n = 21	
	abs.	%	abs.	%	abs.	%	abs.	%	abs.	%
Pulmonary insufficiency	-	0.00	1	6.25	-	-	1	16.67	1	4.76
Pneumosclerosis	1	7.69	-	-	-	-	-	-	1	4.76
Chronic bronchitis	1	7.69	1	6.25	2	9.09	2	33.33	6	28.57
Lung emphysema	1	7.69	-	-	2	9.09	-	-	-	-
Bronchial asthma	-	-	1	6.25	-	-	-	-	-	-

Vision organ examination results

All persons admitted to the clinic have been examined by ophthalmologist. Results are provided by Tables 5.16 and 5.17.

Table 5.16 - Vision examination results in different age groups

Diagnosis	Age, years							
	< 39 n = 10		40 - 49 n = 26		50 - 59 n = 28		> 60 n = 14	
	abs.	%	abs.	%	abs.	%	abs.	%
Vision power decrease	7	70	10	38.46	19	67.86	12	85.71
Eye bottom changes	5	50	10	38.46	21	75.00	11	78.57
Including that of hypertension type	5	50	9	34.62	13	46.43	5	35.71
Including that of sclerosis type	-	-	1	3.85	8	28.57	6	42.86
Cataract	2	20	6	23.08	11	39.29	6	42.86

Table 5.17 – Vision examination results in different occupation duration groups

Diagnosis	Occupation duration, years									
	absent n=13		< 5 n = 16		5 - 9 n = 22		10 - 14 n = 6		> 15 n = 21	
	abs.	%	abs.	%	abs.	%	abs.	%	abs.	%
Vision power decrease	9	69.23	8	50.00	13	59.09	3	50.00	13	61.90
Eye bottom changes	8	61.54	6	37.50	12	54.55	4	66.67	16	76.19
Including that of hypertension type	4	30.77	4	25.00	8	36.36	4	66.67	9	42.86
Including that of sclerosis type	4	30.77	2	12.50	4	18.18	–	–	7	33.33
Cataract	2	15.38	4	25.00	5	22.73	2	33.33	10	47.62

The data demonstrate that all age groups had the decrease of the vision power, retinal angiopathy (of hypertension type) and cataract as well. The retinal angiopathy of sclerotic type was more specific to > 40 year age persons and its incidence rate has increased with age. The relative increase of retinal angiopathy and cataract incidence was noted with the occupation duration.

Digestive system state

The gastrointestinal tract (GIT) was examined in all persons. If necessary, the ultrasound and endoscopy examinations were treated to clarify the pathological findings. GIT examination results are provided by Tables 5.18 and 5.19.

Table 5.18 – Gastrointestinal tract examination results in different age groups

Diagnosis	Age, years							
	< 39 n = 10		40 - 49 n = 26		50 - 59 n = 28		> 60 n = 14	
	abs.	%	abs.	%	abs.	%	abs.	%
Chronic cholecystitis	2	20.00	1	3.85	3	10.71	2	14.29
Chronic gastritis, duodenitis	–	–	4	15.38	4	14.29	3	21.43
Ulceration of stomach and duodenum	–	–	5	19.23	–	–	2	14.29
Chronic colitis	–	–	–	–	1	3.57	–	–
Other	1	10.00	2	7.69	2	7.14	2	14.29

Table 5.19 – Gastrointestinal tract examination results in different occupation duration groups

Diagnosis	Occupation duration, years									
	absent n=13		< 5 n = 16		5 - 9 n = 22		10 - 14 n = 6		> 15 n = 21	
	abs.	%	abs.	%	abs.	%	abs.	%	abs.	%
Chronic cholecystitis	1	7.69	3	18.75	3	13.64	–	–	1	4.76
Chronic gastritis, duodenitis	3	23.08	2	12.50	1	4.55	2	33.33	3	14.29
Ulceration of stomach and duodenum	1	7.69	–	–	3	13.64	1	16.67	2	9.52
Chronic colitis	1	7.69	–	–	–	–	–	–	–	–
Other	2	15.38	3	18.75	1	4.55	–	–	1	4.76

The elaborated examinations certify to the fact that the impact of age and occupation duration is not expressed in GIT pathology.

Surgeon examination results

All persons were observed by surgeon (Table 5.20, 5.21).

Table 5.20 - Surgeon examination results in different age groups

Diagnosis	Age, years							
	< 39 n = 10		40 - 49 n = 26		50 - 59 n = 28		> 60 n = 14	
	abs.	%	abs.	%	abs.	%	abs.	%
Varicose illness	-	-	-	-	2	7.14	2	14.29
Hernias	-	-	1	3.85	-	-	2	14.29
Gallstone disease	-	-	-	-	1	3.57	-	-
Others	-	-	2	7.69	8	28.57	4	28.57

Table 5.21 - Surgeon examination results in different occupation duration groups

Diagnosis	Occupation duration, years									
	absent n=13		< 5 n = 16		5 - 9 n = 22		10 - 14 n = 6		> 15 n = 21	
	abs.	%	abs.	%	abs.	%	abs.	%	abs.	%
Varicose illness	1	7.69	1	6.25	-	-	-		2	9.52
Hernias	1	7.69	-	-	1	4.55	1	16.67	-	-
Gallstone disease	-	-	1	6.25	-	-	-	-	-	-
Others	1	7.69	1	6.25	5	22.73	-	-	7	33.33

Table 5.20 and 5.21 indicate that significant surgical pathology was not found in any age group. The relative increase of surgical pathology incidence in > 40 year age examinees was noted without occupation duration dependence.

Otolaryngologist examination results

Otolaryngologist examinations and audiometry results are described by Tables 5.22, 5.23.

Table 5.22 - Otolaryngologist and audiometrical examination results in different age groups

Diagnosis	Age, years							
	< 39 n = 10		40 - 49 n = 26		50 - 59 n = 28		> 60 n = 14	
	abs.	%	abs.	%	abs.	%	abs.	%
Aural power decrease	1	10.00	6	23.08	15	53.57	10	71.43
Including that for high frequencies	1	10.00	6	23.08	15	53.57	10	71.43
Including that for middle frequencies	1	10.00	1	3.85	4	14.29	6	42.86
Nasopharynx inflammation	1	10.00	7	26.92	7	25.00	5	35.71
Cochlear neuritis. Neurosensorial bradyacuasia	-	-	6	23.08	15	53.57	10	71.43
Tympanic sclerosis	1	10.00	-	-	-	-	-	-

Table 5.23 - Otolaryngologist and audiometrical examination results in different occupation duration groups

Diagnosis	Occupation duration, years									
	absent n=13		< 5 n = 16		5 - 9 n = 22		10 - 14 n = 6		> 15 n = 21	
	abs.	%	abs.	%	abs.	%	abs.	%	abs.	%
Aural power decrease	9	69.23	4	25.00	8	36.36	1	16.67	10	47.62
Including that for high frequencies	9	69.23	4	25.00	8	36.36	1	16.67	10	47.62
Including that for middle frequencies	4	30.77	0	-	3	13.64	1	16.67	4	19.05
Nasopharynx inflammation	1	7.69	6	37.50	8	36.36	2	33.33	3	14.29
Cochlear neuritis. Neurosensorial bradyacuasia	8	61.54	4	25.00	8	36.36	1	16.67	10	47.62
Tympanic sclerosis	1	7.69	-	-	-	-	-	-	-	-

Tables 5.22 and 5.23 demonstrate that routine otolaryngologist examination has revealed the aural decrease of neurosensorial/ conductive character in all age groups. The conductive bradyacuasia was found in < 39 year age group; the neurosensorial bradyacuasia rate was regularly increased in > 40 year age groups. The examination has not revealed the age and occupation duration dependencies for inflammatory changes of membranes and nasopharynx organs. The clear dependence of aural decrease at middle and high frequencies was noted for occupation duration, when applying audiometry tests.

Genitourinary system state

The internist examination has involved examinee complains, urinalysis and USI. 10 examinees were found to have genitourinary system changes. If necessary, these persons were advised by urologist. All these people have got recommendations for out-patient therapy. The revealed diseases are shown by Tables 5.24 and 5.25.

Table 5.24 - Genitourinary system pathology incidence in different age groups

Diagnosis	Age, years							
	< 39 n = 10		40 - 49 n = 26		50 - 59 n = 28		> 60 n = 14	
	abs.	%	abs.	%	abs.	%	abs.	%
Chronic pyelonephritis	1	10.00		-	1	3.57	2	14.29
Chronic cystitis	-	-	1	3.85	-		-	-
Renal concrement disease	-	-	-	-	1	3.57	-	-
Prostate adenoma	-	-	-	-	-	-	2	14.29
Chronic prostatitis	1	10.00	-	-	-	-	1	7.14

Table 5.25 – Genitourinary system pathology incidence in different occupation duration groups

Diagnosis	Occupation duration, years									
	absent n=13		< 5 n = 16		5 - 9 n = 22		10 - 14 n = 6		> 15 n = 21	
	abs.	%	abs.	%	abs.	%	abs.	%	abs.	%
Chronic pyelonephritis	1	7.69	1	6.25	1	4.55	1	16.67	-	-
Chronic cystitis	-	-	-	-	1	4.55	-	-	-	-
Renal concrement disease	-	-	1	6.25	-	-	-	-	-	-
Prostate adenoma	-	-	-	-	-	-	-	-	2	9.52
Chronic prostatitis	-	-	1	6.25	-	-	-	-	1	4.76

Psychophysiological examination results

According to the approved plan, examinees have got psychological testing applying computed diagnostic complex of modified multifactorial method of personality investigation (MMPI-V) including 377 questions as well as operator tests to investigate functional state peculiarities and workability (simple visual-motor reaction, visual-motor reaction of choice, moving object reaction).

The operator test result analysis was automated. Following statistical parameters are calculated: average reaction time, its average quadratic deviation, maximal and minimal reaction time, mode and mode amplitude, number and character of mistakes. The assessment of the workability level was elaborated applying the comparison of testing results versus normal assessment scales of each index. Normal assessment scales were developed according to the statistical analysis of data of normalized sample.

The multifactorial method of personality investigation (MMPI-V) provides the assessment of individual peculiarities of the personality, the presence of accentuations of the character using three assessment scales and ten basic scales. The assessment scales are presumed to assess the sincerity and confidence of data. Basic (clinical) scales provide the assessment of some personality peculiarities; if some scale is expressed, these scales suggest the correspondent accentuation of the character. The initial interpretation of testing result is elaborated by the computer and represented the basis of psychologist conclusion.

78 persons have been examined within the reporting period. According to MMPI, the conditionally normal personality profile was found in 37 persons (47.4%); expressed personality accentuation was found in 11 persons (14.1%); the state of chronic psycho-emotional discomfort was noted in 16 persons (20.5%). In 30 cases (38.5%) results were unconfidently recognized.

When analyzing operator test results, the workability was unchanged in 72 persons (92.3%) increased in 1 person (1.2%),

decreased in 4 persons (5.1%), and strongly decreased in 1 person (1.2%).

The distribution of psychological and psychophysiological indices versus age and occupation duration is demonstrated by Tables 5.32 and 5.33.

Table 5.32 - Psychological and psychophysiological index distribution in different age groups

Indices	Age, years							
	< 39 n = 10		40 - 49 n = 26		50 - 59 n = 28		> 60 n = 14	
	abs.	%	abs.	%	abs.	%	abs.	%
Relative health condition:	MMPI							
Conditionally normal personality profile	3	30.0	14	53.85	–	39.29	9	64.29
Expressed personality accentuation	2	20.0	1	3.85	5	17.86	3	21.43
Unconfident test results	5	50.0	11	42.31	12	42.86	2	14.29
Chronic psycho-emotional discomfort state	2	20.0	4	15.38	6	21.43	4	28.57
Workability:	Operator tests							
Unchanged	9	90.0	24	92.31	26	92.86	13	92.86
Increased	1	10.0	–	–	–	–	–	–
Decreased	–	–	2	7.69	1	3.57	1	7.14
Strongly decreased	–	–	–	–	1	3.57	–	–

Table 5.33 - Psychological and psychophysiological index distribution in different occupation duration groups

Indices	Occupation duration, years									
	absent n=13		< 5 n = 16		5 - 9 n = 22		10 - 14 n = 6		> 15 n = 21	
	abs.	%	abs.	%	abs.	%	abs.	%	abs	%
Relative health condition:	MMPI									
Conditionally normal personality profile	4	30.77	7	43.75	15	68.18	2	33.33	9	42.86
Expressed personality accentuation	2	15.38	3	18.75	2	9.09	2	33.33	2	9.52
Unconfident test results	7	53.85	6	37.50	5	22.73	2	33.33	10	47.62
Chronic psycho-emotional discomfort state	3	23.08	3	18.75	2	9.09	3	50.00	5	23.81
Workability:	Operator tests									
Unchanged	12	92.31	14	87.50	21	95.45	5	83.33	20	95.24
Increased	–	–	–	–	–	–	1	16.67	–	–
Decreased	1	7.69	1	6.25	1	4.55	–	–	1	4.76
Strongly decreased	–	–	1	6.25	–	–	–	–	–	–

Thus, together with the increase of the relative number of unconfident results, the impact of chronic psycho-emotional tension is increased with age. At the same time, the older age group (60 and more tears old) was noted to contain highest number of psychological discomfort people.

Groups of 5-9 year occupation were found to have the relative increase of the incidence rate of chronic psycho-emotional stress as well as the decrease of the number of psychological comfort people.

Operator tests have not revealed significant workability disorders in the majority of examinations. The found changes are basically

within the physiological norm range. The strong decrease of the workability was found in one case only (1.3% of total examinee number) and it was apparently related to the concurrent somatic aggravation. The clear age and occupation duration dependence was not obtained.

The system of clinical and neuro-physiological monitoring of different organs, systems and whole body in employees of jobs with low frequency acoustic oscillation sources has provided the ability:

- To cease the occupational LFAO contact of people with functional disturbances and diseases incompatible with job;
- To have start-up data for followed dynamic observation;
- To reveal functional disturbances of pathological states incompatible with occupation;
- To elaborate scientific analysis and generalization of clinical monitoring data.

The dynamic surveillance of the health status of such cohort certifies to the age dependent increase of pathology incidence in cardiovascular and nervous system, otolaryngology and pulmonary diseases. At the same time, some morbidity incidence increase was noted for bronchi pulmonary, cardiovascular and nervous systems and otolaryngology organs as well in persons of > 10 year occupation.

Psychophysiological examination has revealed significant decrease of adaptive abilities (via operator tests) in > 10 year occupation persons. The decrease of operator workability correlated to the contact time was found. The functional status of regulatory systems (via mathematical analysis of the cardiac rhythm) was worsen within the increase of both age and time of LFAO contact.

Conclusion

The experimental investigation of effect ratio versus frequency and intensity of the affecting infrasound as well as the comprehensive clinical hygienic analysis of industrial infrasound influence are the subject of a number of Russian and foreign studies, which follows from the present monograph, however, only few of these studies are devoted to the infrasound effect mechanism.

At present time, our understandings of the effect mechanism are based upon the extrapolation of noise and vibration mechanism to the infrasound band because of the similar physical nature of these oscillations. Despite the convenience of such approach used by first infrasound studies, it was found that qualitative peculiarity of effects of infrasound and low frequency oscillations makes the discrepancy to models, which satisfactory describe mechanism of noise and vibration effects.

First of all, the way of the infrasound perception is still unclear. Similarly to the noise, the most natural suggestion consists in the aural way of the perception. The fact is obvious that the high exposure level infrasound is aural. The "involvement" of aural system in case of the infrasound exposure is certified not only by the temporal shifts of the aural threshold, but also the cytochemical changes in the receptor cells of the spiral ganglia. The elaborated studies have involved cytochemical shift evaluations (DNA and RNA content) in receptor cells of the spiral ganglia in case of the infrasound exposure; apparently, these studies have demonstrated that noted shifts are not specific but are the reflection of the process of hair cells over-irritation. The localization of shifts was not specific too.

At present time, the intimate processes of the infrasound aural detection are still unclear, though yet 1940th studies have risen the issue of the infrasound perception peculiarities. At < 20 Hz frequencies, the basiliar membrane is not significantly moved even in case of powerful signal because the pre-lymph leaks via helicotrema with the flow speed similar to its move at the time of the oval window movement. The explanation was proposed by E. Wever as follows: the infrasound amplitude is distorted in the aural organ in a such way, where the infrasound signal of higher intensity can give harmonics perceivable by the aural organ.

There are not doubts that the cochlear action of the infrasound is existed. However, is it the single way? Interesting data regarding extra-cochlear perception of the infrasound are provided by studies noted the significant decrease of the swimming time of experimental deaf mice exposed to the intensive ultrasound.

Researchers have observed the nystagmus phenomenon in animals exposed to the intensive ultrasound; apparently, the infrasound perception is arranged via semicircle labyrinth channel receptors. According to this hypothesis, the infrasound pressure changes are transmitted via the middle ear to cochlea pre-lymph and to semicircle channels. The shift of the semicircle channel liquid is resultant, which causes semicircle channel receptor stimulation.

Data confirming the possibility for vestibular manner of the infrasound perception were obtained, when the exhausting of energy and plastic resources of the semicircle cells was found as the infrasound exposure response. It was suggested that the skin mechanical receptors are he significant way of the infrasound perception, as it is for low frequency sounds of high intensity.

The resonance theory of the infrasound effects, which theory is based upon interoceptors and proprioceptors, was popular in infrasound studies; usually, these studies provide resonance frequencies for the whole body and for some organs as well, which frequencies were obtained for the general vibration. However, in case of low frequency acoustic oscillations, the system is more strict if compared to the general vibration and major resonance of "chest wall/abdominal cavity" is noted at 40-60 Hz range in spite of 4-8 Hz in case of vibration. The presence of resonances at these frequencies is experimentally confirmed. However, resonance phenomena can be induced by harmonics accompanying main infrasound frequency.

The resonance theory has to involve the hypothesis of the essential health danger of 7 Hz infrasound, which frequency coincides with α rhythm of the brain currents. Basing upon contemporary understanding of the cerebral electric activity origin, it is difficult to imagine the frequency interaction of processes of such different nature. The experimental confirmation of essential health harm of 7 Hz ultrasound is absent.

Some researchers suggest that infrasound makes the primary impact in intracellular membranes, which disturbs enzymatic activity, essentially biological oxidation and oxidative phosphoring. *In vitro* studies devoted to the assessment of erythrocyte membrane penetration in case of the infrasound exposure have also revealed the increase of the membrane penetration. It is also indirectly certified by the observed hemoglobin count decrease in case of the long term infrasound exposure *in vivo.* The mechanical action of the infrasound and followed change of calcium channel structure was related to the change of constrictive reactions of smooth musculature of portal vein in rats exposed to the infrasound. The significant importance of the membrane penetrative ability is obvious for the infrasound effect mechanism; however, the primary character of this action requires additional explanation.

Thus, the possibility for infrasound perception by aural and vestibular systems is confirmed experimentally and the perception

thresholds are significantly lower for the vestibular system. One can suppose the involvement of other sensorial systems and their interaction in case of the intensive infrasound exposure.

When considering shifts induced by the infrasound exposure, the specific phasic character of reactions is revealed. It is demonstrated that the response to the infrasound exposure is the approximate reaction specific to EEG activation, change of pulse rate and rhythm of cardiac constrictions and breath, which certifies to CNS and whole body reaction to the infrasound independently from the mechanism of the exposure information transfer. After the approximate reaction, the early reaction is developed, which manifests in the decrease of pulse and breath rates with persisting arrhythmia, which elevates with the time course. When assessing vegetative misbalance, the cardiac rhythm response is specific to the increase of the parasympathetic compartment of the vegetative nervous system, which increase is than changed by the phase of the relative decrease. The relative activity increase occurs thereafter.

The phasic character of regulative influences is also confirmed by cholinergic mediation change. The infrasound exposure reaction was the increase of acetylcholinum blood burden and the decrease of acetylcholinum esterase, which was reversed thereafter. In the course of the infrasound exposure, the acetylcholinum burden was increasing and has exceeded control levels at hour 4 of the exposure. Apparently, this phasic character of regulatory reactions is universal.

In case of single exposure to infrasound, the cellular reactions in parenchyma organs were observed including sub-microscopic cellular structure change, which indicates to irreversibility of observed changes.

In case of the long term exposure to the infrasound, deep destructive changes of cells of myocardium, liver, pancreas and brain were observed. Some authors underline the infrasound effects in cellular mitochondrias, which results to the energy process disturbances.

In case of the long term exposure to the infrasound, the albumin metabolism in cells of liver and pancreas was found to be disturbed too as well as the disorder of blood serum albumin fraction ratio.

Both the regeneration and damage processes were noted in chronic experiments, which regeneration was amplified at day 30 after the exposure beginning. At later periods of time, signs of developing adaptation were found.

When comparing the dynamics of rhythm of cardiac constrictions and breath and the ratio of major EEG rhythms during the infrasound exposure, the relative stabilization of the functional status of the organism was found at months 2-3 after the exposure beginning. Within the whole period of the experiment, the relative increase of sympathetic regulation importance was found together with the activity increase of the central regulation of the rhythm,

which can indicate to adaptation. Thus, functional and morphological examination data certify to the possible adaptation to the infrasound exposure together with tension of corresponding regulative mechanisms.

However, the adaptation state is apparently unstable and is close to the pathological state. Morphology examination results indicate that the complete recovery has not occurred in all cases; a portion of damaged cells is degenerated and replaced by the connective tissue.

In case of the chronic infrasound exposure, the involvement of adaptation and accommodation mechanisms was also noted, which is accompanied by the endocrine system tension. However, the adaptation is incomplete and insufficient, which is certified by unfavorable reactions in the organism.

The pathogenesis of developing changes is leaded by the change of functional state of nervous and sympathetic adrenal systems, which results to the internal organ trophicity disturbance.

Thus, the infrasound inflicts serious changes both in metabolism and in major physiological functions. Despite of the unclear intimate mechanism of these processes, the available data give the opportunity to suppose the involvement of aural, vestibular and other sensorial systems together the possible interaction of these systems in case of the intensive infrasound exposure. The peculiar features of the effect of major infrasound frequency and its low frequency harmonics are of specific interest. The cognitive effect is significant for the assessment of thresholds of the approximate reaction, which certifies to CNS and whole organism reaction to the infrasound independently of the effect mechanism. Apparently, the critical systems include CNS, aural and vestibular sensorial systems and cardiac respiratory system. The future development of infrasound reception understanding is necessary because of the importance of this issue for the justification of the critical system (organ) and prospective improvement of the standardization.

Taking into account more that 25 years of original studies of the low frequency acoustic oscillations effects in experimental animals and human, which studies were elaborated under conditions of specialized chambers of variable (dynamic) and low frequency acoustic field in the free space, the following conclusions can be drawn.

1. 1976-2002 comprehensive studies of hygienic, clinical physiological, and experimental character give the opportunity to conclude that low frequency acoustic oscillations are the harmful environmental factor affecting health and workability of human. Therefore, the actuality of the hygienic issue of the infrasound is present and requires future hygienic, medical biological, and pathogenetic research of this poorly known physical factor of the environment.

2. Subjective reactions (especially those described in publications issued in early 1970th) to the low frequency acoustic oscillation exposure (giddiness, nausea, general fatigue, unjustified fear, spatial disorientation, intestinal spasm, fever-like tremor etc) are the clear overestimation. Basic subjective symptoms in case of high pressure levels of infrasound and low frequency acoustic oscillations (up to 155-160 dB) and short exposure time (5-10 minutes) are voice modulation, feeling of chest prelum coinciding to frequency of variable pressure and correspondent breath obstacle or breath rhythm change. Other subjective reactions described in literature seem to be more dependent from psychological state of the complainer rather than to low frequency oscillation themselves.

3. The "non-aural" infrasound has never been contacted by author; it relates to both natural and artificially generated one. Therefore, the attitude of the majority of researchers regarding the absence of "pure" infrasound (i.e. the infrasound non-accompanied by aural sounds, especially of high aural frequencies) in the natural environment seems to be completely valid.

4. The "resonance theory" of the infrasound effects and correspondent "harmful" biological rhythms (like, pulse rate, EEG rhythms or "resonance frequencies of internal organs") are more para-scientific ones; the scientific knowledge of infrasound effects does not involve such issues.

5. Considerations of the specificity of low frequency acoustic effects regarding the possibility for the influence in processing and transfer of the information inside the organism (so-called "information" infrasound effects) were not experimentally confirmed within recent 25 years.

6. The experimental studies of biological effects of LFAO clearly indicate to the necessity to consider two magnitudes (sound pressure and oscillation velocity vector), when examining this exposure and despite dosimetric complications. The assessment only based upon the sound pressure level seems to be erroneous.

7. Until now, pathogenetic mechanism of LFAO reactions of experimental animals and human is not completely clear. The proposed mechanism of diencephalic crisis (Izmerov N.F. et al, 1998), seems to be overestimation of the possible effect grade.

8. At present time, the only fact of significant liquor-hemodynamic and microcirculatory disturbances in lungs, brain and heart is firmly established; in their turn, these disturbances result to hypoxia and followed pathological changes of these organs. The

hypoxia has to be considered as the important pathognomonic consequence of the LFAO exposure. Microcirculatory disturbances are manifested according to the exposure intensity; all kinds of laboratory animals (mice, rats, rabbits, dogs, monkeys, sheep) have got fine spot hemorrhages, blood stasis, erythrocyte aggregation, sludge phenomenon.

When finalizing this monograph, I would like to finish it with the one of philosophical expressions of Kurt Vonnegut, the known American writer. On our view, it is impossible to get the better correlation with a sequence of events and outcomes of examinations described in this book.

"We do not know, where we go, and how we reach, but one is possible to say precisely: when we shall come there - we shall be there, and it is already something significant in itself, even if anything is in it".

(Kurt Vonnegut)

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APPENDIX

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Acoustic Weapons - A Prospective Assessment

Jürgen Altmann[a]

Acoustic weapons are under research and development in a few countries. Advertised as one type of non-lethal weapon, they are said to immediately incapacitate opponents while avoiding permanent physical damage. Reliable information on specifications or effects is scarce, however. The present article sets out to provide basic information in several areas: effects of large-amplitude sound on humans, potential high-power sources, and propagation of strong sound.

Concerning the first area, it turns out that infrasound - prominent in journalistic articles - does not have the alleged drastic effects on humans. At audio frequencies, annoyance, discomfort and pain are the consequence of increasing sound pressure levels. Temporary worsening of hearing may turn into permanent hearing losses depending on level, frequency, duration etc.; at very high sound levels, even one or a few short exposures can render a person partially or fully deaf. Ear protection, however, can be quite efficient in preventing these effects. Beyond hearing, some disturbance of the equilibrium, and intolerable sensations mainly in the chest can occur. Blast waves from explosions with their much higher overpressure at close range can damage other organs, at first the lungs, with up to lethal consequences.

For strong sound sources, mainly sirens and whistles can be used. Powered, e.g., by combustion engines, these can produce tens of kilowatts of acoustic power at low frequencies, and kilowatts at high frequencies. Using explosions, up to megawatt power would be possible. For directed use the size of the sources needs to be on the order of 1 meter, and the required power supplies etc. have similar sizes.

Propagating strong sound to some distance is difficult, however. At low frequencies, diffraction provides spherical spreading of energy, preventing a directed beam. At high frequencies, where a beam is possible, non-linear processes deform sound waves to a shocked, saw-tooth form, with unusually high propagation losses if the sound pressure is as high as required for marked effects on humans. Achieving sound levels which

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would produce aural pain, equilibrium problems, or other profound effects seems unachievable at ranges above about 50 m for meter-size sources. Inside buildings, the situation is different, especially if resonances can be exploited.

Acoustic weapons would have much less drastic consequences than the recently banned blinding laser weapons. On the other hand, there is a greater potential of indiscriminate effects due to beam spreading. Because in many situations acoustic weapons would not offer radically improved options for military or police, in particular if opponents use ear protection, there may be a chance for preventive limits. Since acoustic weapons could come in many forms for different applications, and because blast weapons are widely used, such limits would have to be graduated and detailed.

INTRODUCTION[1]

Acoustic Weapons as Part of "Non-lethal" Weapons

Since the early 1990s there has been an increasing interest - mainly in the U.S. - in so-called non-lethal weapons (NLW) which are intended to disable equipment or personnel while avoiding or minimizing permanent and severe damage to humans. NLW are thought to provide new, additional options to apply military force under post-Cold War conditions, but they may also be used in a police context.[2] Whereas some foresee a military revolution and "war without death,"[3] most others predict or prescribe that NLW would just augment lethal weapons, arguing that in actual war both types would be used in sequence or in parallel.[4] However, there may be situations other than war when having more options of applying force below the threshold of killing could help to prevent or reduce deaths, e.g., in a police context (riots, hostage-taking) or in peace-keeping operations. A range of diverse technologies has been mentioned, among them lasers for blinding, high-power microwave pulses, caustic chemicals, microbes, glues, lubricants, and computer viruses.

Whereas at present it is mainly the U.S. that push research and development of these technologies,[5] a new qualitative arms race in several areas could ensue if they were deployed. There is also a danger of proliferation, which may "backfire" if such new weapons are used by opponents or terrorists.[6] Some concepts would flatly violate existing disarmament treaties, e.g., using microbes as anti-matériel weapons.[7] Others could endanger or violate norms of the international humanitarian law.[8] Thus, there are good reasons to take critical looks at NLW before agreeing to their development and deployment.

Such critical analyses have to consider scientific-technical, military-operational, and political aspects. To some extent, the latter two aspects depend on the first one. Well-founded analyses of the working of NLW, the transport/

propagation to a target, and the effects they would produce, are urgently required. This holds all the more, as the published sources are remarkably silent on scientific-technical detail. Military authorities or contractors involved in NLW research and development do not provide technical information.[9] There are also certain dangers that – absent reliable information – poorly founded views and promises by NLW proponents get more political weight than warranted, or that decisions are being made based on a narrow military viewpoint.

As one general example of such promises note the statement:[10] "The scientists involved in the development of these (NLW, J.A.) technologies know no limits, except funding and support. If they worked at it, they could eventually make it do whatever they needed it to do," a claim that neglects to take into account first, the laws of nature and second, the possibility of countermeasures by opponents.

Since NLW comprise many very different technologies, an in-depth analysis is needed for each type of weapon.[11] The present article presents an analysis of acoustic weapons, with an emphasis on low-frequency sound. Such weapons have been said to cause, on the one hand, disorientation, nausea, and pain without lasting effects. On the other hand, the possibility of serious organ damage and even death has been mentioned – thus the "non-lethal" label does not hold for all possible types and uses. Table 1 lists a few allegations concerning acoustic weapons. Because many of these are based on hearsay and not on publicly documented cases, they cannot be taken as reliable information, but rather as indicators of directions where independent analysis is needed.

Table 1: Selected examples of alleged properties, effects, and targets of acoustic weapons from the available literature; not often are sources given. Note that there are some inconsistencies, as, e.g., whether high or very low frequencies are used in "acoustic bullets" (refs. 18-21). In some cases one cannot avoid the impression that the respective author/s misunderstood something or mixed things up, as, e.g., with the plasma created by an acoustic bullet or with equalling non-diffracting with non-penetrating (ref. 18). [12] ARDEC: U.S. Army Armament Research, Development and Engineering Center, Picatinny Arsenal NJ, U.S., LANL: Los Alamos National Laboratory, Los Alamos NM, U.S., SARA: Scientific Applications and Research, Huntington Beach CA, U.S.

Sound Source	**Effects**	**Targets**	**Ref.**
Infrasound	May affect labyrinths, vertigo, imbalance, etc.; resonances in inner organs, e.g., heart, with effects up to death	Riot control (British use in Northern Ireland)	13
Infrasound from non-linear superposition of two ultrasound beams (tested in Great Britain)	Intolerable sensations	Riot control	14
Infrasound	Incapacitation, disorientation, nausea, vomiting, bowel spasms; effect ceases when generator is turned off, no lingering physical damage	Crowd/riot control, psychological operations	15
Very low frequency noise	Disorientation, vomiting fits, bowel spasms, uncontrollable defecation	Enemy troops	16
Infrasound - tuned low frequency, high intensity	Anti-personnel: resonances in body cavities causing disturbances in organs, visual blurring, nausea - temporary discomfort to death. Anti-material: embrittlement or fatigue of metals, thermal damage or delamination of composites; against buildings: shattering of windows, localized earthquakes		17

Sound Source	Effects	Targets	Ref.
Infrasound from banks of very large speakers and high-power amplifiers not yet existing, requiring new cooling design and new materials	Discomfort, disorientation, nausea, vomiting	Hostage rescue, crowd/riot control, psychological operations	18
High-power, very low frequency acoustic beam weapon, being developed in conjunction with SARA, by ARDEC and LANL; phased-array setup allows smaller size, about 1 m^3 (on small vehicle); smaller later in the future	Discomfort like standing near large air horn (certain frequencies and intensities)	Protect U.S. overseas facilities (e.g., embassies), riot control	19
Very low frequency acoustic bullet, emitted from antenna dishes, being investigated at ARDEC		Offensive capability against personnel in bunkers or vehicles	20
High-power, very low frequency acoustic bullets from 1-2 m antenna dish	Incremental effects from discomfort to death		21
High-frequency, non-diffracting (i.e., non-penetrating) acoustic bullet creates plasma in front of target	Blunt-object trauma		19
Baseball-sized acoustic pulse, about 10 Hz, over hundreds of meters, developed in Russia	Selectable from non-lethal to lethal levels		22
"Deference tone" at intersection of two otherwise inaudible beams, developed in Russia			22

Some Historic Aspects of Acoustic Weapons

Whereas low-frequency sound was often used passively by armed forces to detect and locate artillery, nothing is known about actual weapon use by the military. Two infrasound review articles mention that there are indications that Great Britain and Japan had investigated this possibility, and then demonstrate that for *lethal* use over some distance unrealistically high source powers would be required.[23]

With respect to *non-lethal* use of low-frequency sound, already a 1969 book on riot control mentioned that the theory of using sound as a weapon had been discussed in many scientific articles (which, however, the present author cannot confirm), that super- and subsonic sound machines had been tested for riot control, and that these machines had generally turned out to be too costly,

too cumbersome and too unfocused.[24] The only sound device discussed in some detail, the "Curdler" or "People Repeller" was said to emit shrieking, pulsating sound that, amplified by a 350-W amplifier, produced 120 dB at 10 m distance.[25]

In 1971 a short survey from the British Royal Military College of Science mentioned reducing resistance to interrogation, inducing stress in an enemy force, creating an infrasonic sound barrier and rapid demolition of enemy structures.[26] Somewhat later, the journal *New Scientist* - in the context of reporting on weapons used by the British Army against protesters in Northern Ireland - wrote about successful tests of the "squawk box," a device said to emit two near-ultrasound frequencies (e.g., at 16.000 and 16.002 kHz) which would then combine in the ear to form a beat frequency of, e.g., 2 Hz, said to be intolerable.[27] The Ministry of Defence denied the existence of the device.[28] A later book assumed that it had never been fully developed.[29] (For a discussion of this possibility, see 5.1.2 below).

At the same period, there was a series of articles stating marked effects of infrasound such as dizziness and nausea at levels between 95 and 115 dB which other experimenters, however, could not confirm.[30]

U.S. forces used loud music to force M. Noriega out of his refuge in Panama in 1989.[31] Since such sound applications work rather by annoying than by physical damage, they will not be further discussed here.

Actual Developments

The US Army Armament Research, Development and Engineering Center (ARDEC) at the Picatinny Arsenal, New Jersey, is responsible for the Army effort in the Low Collateral Damage Munitions programme.[32] One project in low-frequency acoustics is a piston- or explosive-driven pulser forcing air into tubes to produce a high-power beam, to be applied against small enclosed volumes; another deals with the possibility of projecting a non-diffracting acoustic "bullet" from a 1-2 m antenna dish using high-frequency sound. Both were to be done by Scientific Applications and Research Associates (SARA) of Huntington Beach, California.[33] Similar projects seem to be underway in Russia: in a Center for the Testing of Devices with Non-Lethal Effects on Humans in Moscow, long-time U.S. NLW proponents J. and C. Morris were reportedly shown a device propelling a baseball-sized acoustic pulse of about 10 Hz over hundreds of meters, scalable up to lethal levels. Another principle was a "defference" (probably difference) tone produced at the intersection of two otherwise inaudible beams.[34] (For a discussion of acoustic bullets and generation of audible or infrasound from two ultrasound fields, see 5.1.3 and 5.1.2 below).

As with the U.S. projects, reliable public information is not available.

The most specific information available at present seems to be contained in the first few pages of a SARA report of 1996,as reported in a recent overview article:[35]

- With respect to effects on humans, some of the allegations are: Infrasound at 110-130 dB would cause intestinal pain and severe nausea. Extreme levels of annoyance or distraction would result from minutes of exposure to levels 90 to 120 dB at low frequencies (5 to 200 Hz), strong physical trauma and damage to tissues at 140-150 dB, and instantaneous blast-wave type trauma at above 170 dB (for an explanation of the level unit decibel see below). At low frequencies, resonances in the body would cause hemorrhage and spasms; in the mid-audio range (0.5-2.5 kHz) resonances in the air cavities of the body would cause nerve irritation, tissue trauma and heating; high audio and ultrasound frequencies (5 to 30 kHz) would cause heating up to lethal body temperatures, tissue burns, and dehydration; and at high(er?) frequencies or with short pulses bubbles would form from cavitation and micro-lesions in tissue would evolve.
- Under development are a non-lethal acoustic weapon for helicopter deployment (tunable 100 Hz to 10 kHz, range above 2 km, goal 10 km), a combustion-driven siren on a vehicle (multi-kilowatt power, infrasound), and an acoustic beam weapon for area denial for facilities housing weapons of mass destruction using a thermo-acoustic resonator, working at 20-340 Hz.
- Using combustion of chemical fuel, scaling up to megawatt average power levels would be possible, with fuel tank storage capability - at fixed sites - for a month or more.
- Acoustic weapons would be used for US embassies under siege, for crowd control, for barriers at perimeters or borders, for area denial or area attack, to incapacitate soldiers or workers.

It should be noted that several of the claims about effects do not stand critical appraisal, in particular for the infrasound and audio regions.[36] The same holds for a range of kilometers.[37] It seems that SARA have taken earlier allegations at face value without checking their correctness.[38]

In Germany, Daimler-Benz Aerospace (DASA), Munich, has done a detailed study of all kinds of non-lethal weapons for the Ministry of Defence in 1995. Whereas most of the descriptions of technologies and effects are sound, the section on acoustic weapons contains errors.[39] Recently, the German

Fraunhofer Institute for Chemical Technology was tasked to develop a prototype and test the deterring effect of strong sound.[40]

Goals of This Article

To my knowledge, acoustic weapons have not been the subject of detailed public scientific analysis. They were discussed in a section of a 1978 book and a 1994 conference contribution, both motivated by humanitarian-law concerns; these, however, are rather short and non-quantitative.[41] A recent article is significantly more comprehensive, but relies heavily on general statements from a firm engaged in developing acoustic weapons, the defence press, and military research and development institutions. The author calls for a "much more sophisticated and fuller understanding of the damage caused by high power acoustic beams" and asks the humanitarian-law community to involve itself in the assessment and debate.[42]

The present article is intended to contribute to that goal by presenting more, and more reliable, information, so that serious analysis of military-operational, humanitarian, disarmament, or other political aspects need not rely on incomplete or even obscure sources.[43]

This study is based on the open literature and my own theoretical analysis, without access to scientific-technical data gained in acoustic-weapons research and development and without original experiments. Something may have been overlooked; at some points speculation is unavoidable; and some questions will remain open, hopefully to be answered by future work.
The questions to be answered are the following:

- What are the effects of strong, in particular low-frequency, sound on humans?
- Is there a danger of permanent damage?
- What would be the properties of the sound sources (above all, size, mass, power requirement)?
- How, and how far, does strong sound propagate?
- Can we draw conclusions on the practical use by police or military?

The following subsection gives a few general remarks on acoustics. The major sections deal with effects of strong sound on humans, production of strong sound, protective measures, and therapy. Finally, preliminary conclusions are given. The appendix mentions, first, some properties of pressure

waves in air. Second, allegations concerning acoustic weapons made in journalistic articles are analyzed.

General Remarks on Acoustics

In a broad sense, any variation of air pressure in time constitutes sound. For a sinusoidal time course, the number of repetitions per time unit is called the frequency, measured in Hertz = 1/second. Usually, the frequency region below 20 Hz is called infrasound, but this is not an absolute hearing limit - sounds with lower frequencies can be heard and otherwise perceived if the pressure is high enough. To prevent misunderstanding with the term "audible," in this article the range from 20 Hz to 20 kHz will be called "audio." The hearing, pain, and damage thresholds decrease with increasing frequency between a few Hz and 20-250 Hz (see figure 2 below); thus low-frequency effects will be much stronger at low audio frequencies than with infrasound proper. Therefore, despite the emphasis on infrasound in the journalistic articles, here the range from 1 to 250 Hz is denoted by "low frequency" and treated in common. For frequencies above 20 kHz, the usual term "ultrasound" will be used.

Pressure variations mean deviations from the average air pressure toward higher and lower values, denoted by over- and underpressure. Usually these deviations are much smaller than the air pressure; they are called sound pressure. Because sound pressure and intensity vary over many orders of magnitude, and because the human loudness sensation is approximately logarithmic, these physical quantities are often given as levels L in a logarithmic scale, in decibel units, where

$$L_p = 20\log(p_{rms}/p_{ref})\,dB \quad and \quad L_I = 10\log(I_{rms}/I_{ref})\,dB \qquad (1)$$

p_{rms} and I_{rms} are the respective root-mean-square values of sound pressure (deviation from static air pressure, measured in Pascal) and sound intensity (acoustic power per area, proportional to sound pressure squared, measured in Watt/square meter). A ten-fold increase in pressure means a hundred-fold increase in intensity and an increment of 20 dB in level. For the reference values, in acoustics usually

$$P_{ref} = 20\mu Pa \quad and \quad I_{ref} = 10^{-12}\,W/m^2 \qquad (2)$$

are chosen. These values are about the human hearing threshold at 1 kHz, close to the frequency of highest sensitivity; thus with equation (A-2) and an acoustic air impedance of $\rho_0 c_0 \sim 400$ kg/(m^{2}s) under normal conditions both

levels, for pressure and intensity, are equal.[44] Levels will usually refer to these values in this article; frequency-weighted level scales incorporating human sensitivity, such as the dB(A), when used, will be denoted as such.

The most important properties of pressure waves in air are mentioned in appendix 1. For sound pressures which are not extremely strong - below maybe 100 Pa (level 134 dB), 0.1 % of normal pressure -, the effects can be described by linear equations. The sound speed is constant, and the superposition principle holds as, e.g., in optics (linear acoustics). At higher values, but still below atmospheric pressure, the increase of propagation speed with pressure becomes important, and waves become steeper as they propagate, but the underpressure is about the same as the overpressure and the propagation speed remains the same as with small amplitudes (non-linear acoustics, weak-shock formation). Such non-linear effects would be important in the conversion of frequencies that has been alleged to take place with acoustic weapons. If the overpressure is larger than the pressure at rest, as, e.g., with blast waves from explosions, the shock speed becomes much faster, and the underpressure can no longer be of equal amplitude (strong shock). It seems problematic to count a blast-wave weapon as an "acoustic" one, otherwise many types of explosive shells, bombs, or fuel-air explosives would come under the same heading.[45] However, for the sake of completeness, because of a smooth transition from one to the other, and because blast waves have been mentioned in this context,[46] strong shock is included into the present considerations.

Effects of Strong Sound on Humans[47]

Strong sound can temporarily or permanently reduce the hearing ability and affect the vestibular organ. At extreme levels, physical damage to organs of the ear can occur even with short exposure. At even higher levels, occurring practically only in overpressure pulses from explosions, other organs are injured, with the lung as the most sensitive one.

In this section, a few general properties of the ear and damage to it are described first. In the following parts, special emphasis is put on low frequencies because their effects are less known than in the audio region, and because they are mentioned in many publications on acoustic weapons. High-frequency audio sound and ultrasound are covered rather briefly. A special subsection treats shock waves, e.g., from explosive blasts.

Table 9 at the end of this section gives a simplified summary of the various effects in the different frequency ranges.

General Remarks on the Ear[48]

Hearing and Hearing Damage

In the human ear (figure 1), sound waves entering the ear canal set the eardrum into vibration. This motion is coupled by the three middle-ear ossicles to the oval window at the beginning of the labyrinth. The resulting pressure wave travelling in the cochlear perilymph bends the basilar membrane which separates the cochlea longitudinally into the scala vestibuli and the scala tympani; these two canals are connected at the cochlea tip, and the latter one leads back to the round window at the middle ear. The basilar membrane carries the organ of Corti the hair cells of which sense the deformation and relay this information via ganglion cells to the brain. The Eustachian tube connects the middle ear and the nasal cavity. Linked to the cochlea are the cavities and three semicircular canals of the vestibular organ which senses head motion and helps maintaining equilibrium.

The middle ear contains mechanisms that can reduce the amount of vibration coupled to the inner ear, thus defining the limits of hearing and reducing damage from strong sound. At very low frequencies, the Eustachian tube can provide pressure equalization. The aural reflex, which contracts muscles (m. tensor tympani and m. stapedius) in the middle ear about 0.2 s after the onset of strong noise, weakens the transmission of the ossicles. Due to the mechanical properties of the ossicles, frequencies above about 20 kHz are not transmitted.

After exposure to strong sound the auditory system usually becomes less sensitive; in other words the threshold of hearing is shifted to higher levels. Recovery is possible if the exposure is below frequency-dependent limits of sound level and duration, and if the following rest period is sufficient. This is called temporary threshold shift (TTS) and is usually measured 2 minutes after the noise ended. Up to TTS levels of about 40 dB, recovery is smooth and mostly finished within 16 hours. Beyond certain limits, recovery is incomplete and permanent threshold shifts (PTS), i.e., permanent hearing losses, remain. Because this so-called "noise-induced hearing damage" is somehow cumulative, exposure criteria have to include the duration and recovery time beside spectral composition and level.[50]

Whereas TTS can be studied with humans in experiments, for PTS one has to rely on people injured by accident, occupational noise or the like. The other method is to do animal experiments - the results of which of course can-

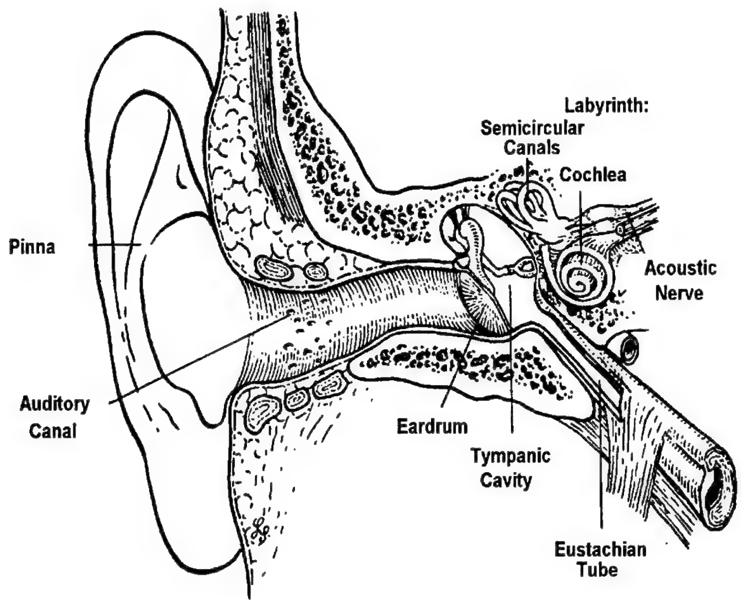

Figure 1: The human ear consists of three parts: external, middle, and inner ear. Sound waves reflected by the pinna and travelling in the auditory canal produce vibration of the eardrum (tympanic membrane). The three middle-ear ossicles (malleus, incus, and stapes) transfer this motion - increasing the pressure - to the oval window at the entrance of the labyrinth and to the perilymph inside. The resulting pressure wave travels into the cochlea, bending the basilar membrane which separates the cochlea longitudinally and carries the sensory hair cells. Their excitation is relayed to the brain by the acoustic nerve. Pressure equalization of the middle ear is possible via the Eustachian tube. The middle-ear muscles (not shown) can reduce the transmission of the ossicular chain. The second part of the labyrinth is the vestibular organ with its cavities and semicircular channels for sensing motion. (Modified from ref. 49, used by permission of authors and publisher; original copyright: Springer-Verlag).

not directly be applied to humans. As animal species for model systems, often chinchillas, guinea pigs, or cats are selected, thought to be more sensitive than humans; but also dogs, monkeys, and for blast waves sheep have been used.

Which noises will produce more PTS (for higher level and/or longer duration) can be predicted on the basis of the TTS. There are complicated schemes to quantitatively estimate PTS from noise via expected TTS, reasoning that the PTS after 20 years of near-daily exposure is about the same as the TTS after 8 hours. PTS is thought to be produced by mechanical and metabolic processes damaging the sensory hair cells on the basilar membrane of the

cochlea. PTS – as well as TTS – is relatively variable between subjects. Usually, it develops first and strongest at 4 kHz, then spreading to lower and higher frequencies, relatively independent of the noise spectrum at the workplace. There is a considerable amount of literature on all aspects of hearing damage, such as measuring and documenting it, understanding the physiological mechanisms, estimating the risks quantitatively, recommending limits for preventive measures, considering acceptable damage, and percentages of people affected. Most concerns are on cumulative effects of many years of exposure as, e.g., in the workplace, where PTS has been found at levels below 80 dB(A), but usually it is the range from 80 to 105 dB(A) that matters. There is, however, also injury produced by one or a few short-term exposures to strong sound - this often comes under the name "acoustic trauma."[51] Its inner-ear effects range from some disarray of the hairs of the hair cells to complete destruction of the organ of Corti. Secondarily, ganglion cells and nerve fibres may degenerate.

Figure 2 shows the human hearing threshold and curves of equal perceived loudness from very low to high frequencies.[52] As can be seen, perceived loudness, measured in phones, increases about logarithmically with sound pressure at each frequency. Also drawn are thresholds for damage effects to the auditory system which are important for judging acoustic weapons:

- Thresholds of hearing hazard – above the first one there is a danger of permanent hearing loss under certain conditions – noise level, duration, number and schedule of exposures, variables of the individual. Close to the threshold, the duration may amount to several hours of daily exposure over many years. Above the second threshold, at 120 dB where discomfort begins, there is a high risk of hearing loss even for short and few exposures (except impulse sounds).

- Aural pain – this occurs above about 140 dB (200 Pa) throughout the audio region. However, in the infrasound range the threshold increases with falling frequencies to 160 and 170 dB (2 and 6 kPa). For static pressure, pain occurs above about 173 dB (9 kPa) of underpressure and about 177 dB (14 kPa) of overpressure. Pain is thought to occur when the mechanical limits of the middle-ear system are transcended, and it is not directly connected to sensitivity or hearing damage: damage can occur without pain and vice versa. However, under normal conditions exposure should be stopped when pain is felt.

- Eardrum rupture – the threshold is at about 160 dB (2 kPa) in the audio region. For a step to a static overpressure the threshold is at 186-188 dB

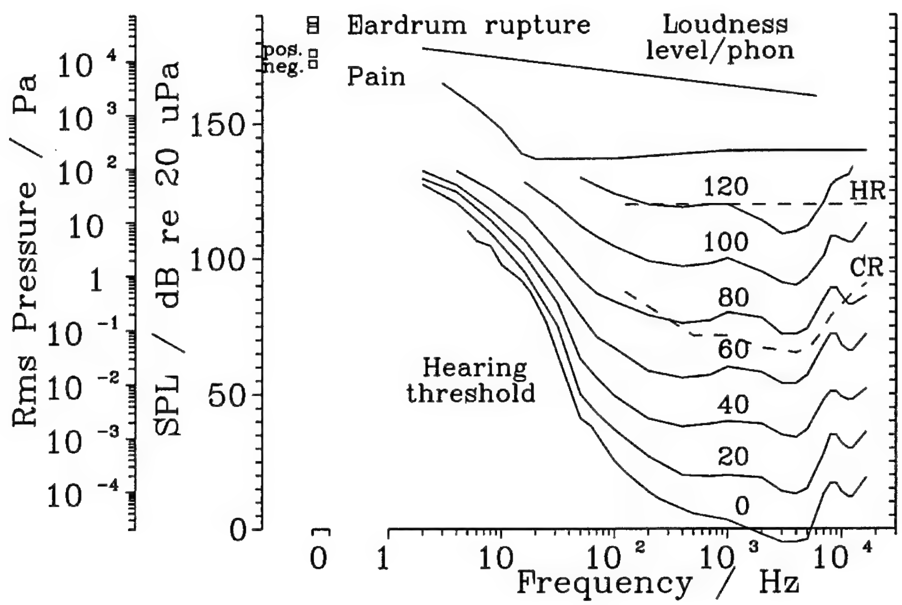

Figure 2: Threshold of hearing (corresponding to 0 phone), curves of equal perceived loudness for 20, 40, 60, 80, 100, and 120 phones, rms sound pressure (logarithmic scale) and its level versus frequency. The threshold values are for binaural hearing of pure tones; monaural perception thresholds are higher. Also given are the thresholds of conditional (CR) and high (HR) risk of permanent hearing loss (dashed), of aural pain and of eardrum rupture. The high-risk threshold is also valid for the feeling of discomfort; the threshold for tickle sensation is slightly below the one for pain. Especially for eardrum rupture, the threshold is only roughly known. On the left, pain and eardrum rupture thresholds are shown for static pressure. For pain, the values for over- (pos.) and underpressure (neg.) are slightly different. Note that normal atmospheric pressure is 101 kPa.[53]

(42- 55 kPa peak). Even though membrane ruptures usually heal, damage to the middle and inner ear may remain. However, rupture serves as a kind of fuse, reducing the pressure transmitted to the inner ear, and thus the potentially permanent inner-ear damage.

Vestibular System

The vestibular system of the inner ear contains cavities (utricle and saccule) with sensors for linear accelerations and three semicircular channels for sensing angular accelerations. The vestibular system causes – via several, mostly

sub-conscious channels in the central nervous system – eye movements and postural changes, and provides perception of motion and orientation. The vestibular system is one of the sensor modalities responsible for motion sickness (the other two, the visual and somatosensory systems, are less relevant in the present context).

The liquids (endolymph and perilymph) in the vestibular organs are connected to those in the spiral cochlea. Thus, acoustic stimulation of the balance organs is possible in principle, and this would be the mechanism for the alleged production of vertigo and nausea by infrasound. Effects and thresholds observed with humans and animals are discussed below for the different frequency ranges.

Effects of Low-Frequency Sound

In the 1960s and 1970s there was a wave of ascribing exaggerated effects to infrasound, not only in the general press.[54] Much of this was anecdotal. In some cases, effects observed in one laboratory could not be reproduced in another. One reason may be production of harmonics in test systems.

Hearing Threshold and Loudness Perception at Low Frequencies

Hearing does not abruptly stop below 20 Hz. As careful measurements have shown, with high enough sound pressure the ear can register infrasound down to about 1 Hz. However, below about 50 Hz the hearing threshold increases steeply with falling frequency, as evident in figure 2.[55] At lower frequencies, the equal-loudness curves lie much closer; this means that loudness perception increases much faster with sound pressure level than at higher frequencies. Also the pain threshold is closer to the hearing threshold at low frequencies.

High-Intensity Effects of Low-Frequency Sound on Ear and Hearing

The human auditory system seems to be relatively tolerant of low-frequency exposure, especially with infrasound where even at very high levels only some TTS and no PTS occurs (table 2). Infrasound even reduces TTS from high-frequency noise because (quasi-)static loading of the middle ear reduces its transmission to the inner ear. It is likely that PTS observed, e.g., in people exposed to low-frequency noise at the workplace is mainly due to higher frequencies also present.

Table 2: Auditory effects of low frequency sound in humans. Note that chinchillas, much more sensitive in the audible range, showed clear middle and inner ear damage after exposures to frequencies between 1 and 30 Hz at levels 150-172 dB.

Frequency /Hz	Level / dB	Duration	Effect
<1 - 20	125-171	minutes	often TTS at audio frequencies, recovery within 1/2 hr
3 or 23	130	1 h	no TTS
Low audible	90	many hours	TTS, recovery after up to 2 days
" 40	140-150	0.5-2 min	no PTS
Simulated airbag inflation:			
Infrasound part (c. 5 Hz)	165 peak	0.4 s	no TTS
High-frequency part (0.5-1 kHz)	153 rms	0.4 s	TTS 5-8 dB at 1.5-12 kHz
Both parts together	c. 170 peak	0.4 s	TTS 2-3 dB at 1.5-12 kHz
Sonic boom (mainly 2-20 Hz)	162-171 peak	seconds	no PTS

Of course, threshold shifts are not immediately felt by the individual and are thus irrelevant as weapons effects, at least as far as the weapon designers and users are concerned. More relevant will be a pressure sensation, which develops at about 130 dB, independent of frequency. Even more impressive will be pain in the ear which sets in between 135 and 162 dB depending on frequency, see figure 2. The human eardrum ruptures above 42-55 kPa static pressure change (186-189 dB). Since for audio frequencies, the threshold is assumed to be well over 160 dB (2 kPa), infrasound should lie somewhere in between.[57]

High-Intensity Effects of Low-Frequency Sound on the Vestibular System

Vestibular excitation can be measured by reflexively produced eye movements (nystagmus) or, with humans, by performance in balancing tests. Neither in animals nor in humans were effects observed from infrasound at 130 to 172 dB. Thus, the vertigo and nausea effects in the journalistic articles ascribed to

intense infrasound cannot be confirmed. On the other hand, low audio frequencies of 50-100 Hz at 150 to 155 dB caused mild nausea and giddiness.

High-Intensity Effects of Low-Frequency Sound on the Respiratory Organs

Strong infrasound of 0.5 Hz can act like artificial respiration. Exposure to sonic booms (main energy in the infrasound region) between 154 dB (1.0 kPa) and 171 dB (6.9 kPa peak) did not lead to adverse effects on the human respiratory system.

In the low audio frequency region below 50 Hz, exposure to levels up to 150 dB (0.63 kPa) caused chest-wall vibration and some respiratory-rhythm changes in human subjects, together with sensations of hypopharyngeal fullness (gagging); these effects were felt as unpleasant, but clearly tolerable. Between 50 and 100 Hz, however, subjective tolerance was reached and exposure discontinued at 150 to 155 dB (0.63 to 1.1 kPa); respiration-related effects included subcostal discomfort, coughing, severe substernal pressure, choking respiration, and hypopharyngeal discomfort.[58]

Other High-Intensity Effects of Low-Frequency Sound

Several other effects were observed during exposure to intense low-frequency (30 to 100 Hz) sound at levels around 150 dB. Among these were increased pulse rates, cutaneous flushing, salivation and pain on swallowing. The visual field vibrated and acuity was reduced. Subjects showed marked fatigue after exposure. On the other hand, brief infrasound had no effect on visual acuity, motor tasks and speech production.

Vibration Considerations

It is sometimes maintained that infrasound sets organs in motion similarly to external vibration applied to the body. Whereas there are similarities, there are also important differences.

For vertical vibratory excitation of a standing or sitting human body, below 2 Hz the body moves as a whole. Above, amplification by resonances occurs with frequencies depending on body parts, individuals, and posture. A main resonance is at about 5 Hz where greatest discomfort is caused; the reason is in-phase movement of all organs in the abdominal cavity with consequent variation of the lung volume and chest wall.[59]

Conditions are different when slow air pressure variations impinge on the human body. At low frequencies where the body dimensions are smaller than the wavelength, e.g., above 2 m for frequencies below 170 Hz, the same momentary pressure applies everywhere, and the tissue behaves as a viscoelastic fluid with much lower compressibility than air.[60] This produces some

vibration, but due to the large impedance mismatch nearly all energy is reflected. The exceptions are where enclosed air volumes render the body surface softer, as in the ear, where 90 % of the impinging energy is absorbed, or at the lungs, where the chest wall or the abdomen can move more easily if external pressure/force is applied. Because the external pressure simultaneously produces air flow through the trachea into and out of the lungs, the inner pressure counteracts the chest wall and abdomen movements. The system acts much more stiffly than with unidirectional vibratory excitation, and the resonance (with the highest velocities per sound pressure and thus highest tissue strains) is at 40 to 60 Hz instead of one tenth of that value.

Effects of High-Intensity High-Frequency Audio Sound

Effects on Ear and Hearing

PTS is mainly seen and studied with occupational exposure over a decade and more, from weighted levels of below 80 dB(A) to usually less than 120 dB(A). The sensitivity to TTS and PTS follows roughly the loudness contours. In the present context, however, the questions relate to short exposures at potentially higher levels.

Concerning the danger of permanent damage from a single or few exposures (acoustic trauma), there are understandably not many experimental studies with humans. In order to estimate expected effects one can evaluate related TTS experiments, use damage criteria gained from the parallelism between TTS and PTS, and draw cautious conclusions from animal experiments. Table 3 shows that short exposures at high levels need not produce PTS in humans. Table 4 shows the results of PTS experiments on animals.

Table 3: Auditory effects of high-frequency audio sound on humans. At higher audio frequencies, humans are much less susceptible than around 1 kHz.

Frequency / kHz	Level / dB	Duration	TTS	PTS	Remarks
0.1, 1, 2, 4	110, 120, 130	1 - 64 min	strongest at 4 kHz, much less at 1 and 2 kHz, even less at 0.5 kHz; recovery from 60 dB TTS in up to 5 days	no evidence	
0.25 - 5.6	up to > 140	many seconds		obviously none	testing for tickle and pain thresholds
Broadband noise (0.5-1 kHz, simulated airbag inflation)	153 rms	0.4 s	TTS 4-8 dB at 1.5-12 kHz, vanished after minutes	none	young, healthy men
Jet afterburner noise	> 140	seconds at a time		no consistent PTS after several months	flight-deck/ airfield ground personnel
9 - 15	140 - 156	5 min	TTS at exposure frequencies and half of those, fast recovery	none	

Table 4: PTS and physiological damage produced by high-frequency audio sound in animals. With the cat experiments, at all frequencies a 10-dB increase marked the transition from minimal to severe destruction in the cochlea.

Animal	Frequency / kHz	Level / dB	Duration	PTS	Physiological damage
Chinchilla		~ 120	~ 1 h		damage to hair cells, etc.
Guinea pig	0.19 -8.0	135-140	few minutes		severe hair cell injury
		>40	few minutes		organ of Corti destroyed at respective most affected site
Cat	0.125	150	4 h	none	hair cell losses in general-paralell to functional deficiencies
		153-158	4 h	partially/ fully deaf	
	1.0	120	1 h	none	
		130	1 h	55 dB at 2kHz	
		140	1 h	deaf at all frequen-cies	
	2.0	140	1 h	deaf at ≥ 2 kHz	
	4.0	135	1 h	none	
		140	1 h	60 dB at 4 kHz	

Acoustic trauma for short exposures occurs above some critical combination of level and duration which corresponds to a kind of "elastic limit" of the organ of Corti. In chinchilla and guinea pig experiments extensive damage was about the same if the duration times the intensity squared was constant, i.e., for each 5 dB level increase the duration has to be divided by 10. Assuming the same law to hold for humans, and taking the critical value separating some hearing loss from acoustic trauma from guinea pigs which are closer to the human sensitivity, e.g., 7 minutes of 135 dB, one would arrive at alternative combinations of 40 s exposure to 140 dB, 4 seconds to 145 dB, and 0.4 seconds to 150 dB.[61] Thus it seems advisable to assume that a singular exposure at the pain threshold in the audio range (140 dB) will become dangerous, i.e.,

produce marked PTS in the majority of the people affected, after about half a minute, and above that at progressively shorter intervals.

Eardrum rupture at high audio frequencies is expected above a threshold of over 160 dB (2 kPa).[62]

Non-Auditory Effects of High-Intensity High-Frequency Audio Sound

Vestibular responses in humans are elicited by audio sound above about 125 dB. At levels about 140 dB near jet engines, an equilibrium disturbance was felt at critical rotation rates. Though these authors quote several oral communications about similar effects and though they themselves have been quoted often, it seems that the conditions and causes have not been analyzed thoroughly.[63] High-level effects in animals range from eye movements to severe lesions in the vestibular organs. With high-frequency audio sound, no adverse effects on respiration are to be expected, since the pressure changes occur much too fast for significant motion of either body walls and organs, or the air in the trachea. However, resonances in the opened mouth, the nasal cavities or sinuses may produce a sense of touch or tickling above 120 dB.

At levels of 160 dB and higher, heating becomes relevant. Whereas absorption is small on naked skin due to the impedance mismatch, it becomes strong wherever strong friction impedes the air movement, as in textiles, hair, fur, or narrow ducts. Since levels above 140 dB in the high-frequency audio region are extremely rare, and people in the workplace need to be protected because of their ears in the first place, it seems that auditory as well as non-auditory injury due to such noise has practically not been described.[64]

Effects of High-Intensity Ultrasound

Around 1950, there was increased talk and fear of "ultrasonic sickness" connected with symptoms of headache, nausea, fatigue etc. experienced by personnel working in the vicinity of the newly-introduced jet aircraft. Later, similar complaints came from people working with washers and other ultrasound equipment in industry. It seems, however, that these effects were rather caused by high- and sometimes low-frequency audio noise simultaneously present.

Auditory Effects of Strong Ultrasound

The upper threshold of hearing varies between subjects and decreases with age. Whereas using bone conduction aural effects can be elicited, airborne ultrasound (above 20 kHz) cannot be heard by nearly all people and does not

have a marked effect on the human ear. When subjects were exposed to the high audio frequency of 17 kHz and ultrasound ones of 21 to 37 kHz at levels as high as 148 to 154 dB, there was some TTS at the first sub-harmonics (half frequency) and, for the higher two excitation frequencies, also at the second ones. These shifts vanished rapidly and no PTS remained.

Considering the non-linear production of sub-harmonics observed in electrophysiological recordings from guinea pigs and chinchillas, an extension of damage-risk criteria to the ultrasound region was proposed with a limit of 110 dB.

Non-Auditory Effects of Strong Ultrasound

In an analysis of ultrasonic washers and drills, in the vicinity of which workers had experienced fatigue, headaches, tinnitus, and nausea, it turned out that there were considerable levels at audible frequencies as well which were identified as the probable causes. No vestibular effects were reported with the TTS tests at up to 154 dB. Respiratory effects are again not to be expected because of the fast pressure changes.

At extreme levels, close to a siren of maximum 160-165 dB, tickling in mouth and nose was observed with ultrasound as with high-frequency audio sound. For such levels, as with high audio frequencies, heating will occur mostly in narrow passages and other places of high friction.[65] Above, heating will be felt at naked skin as well.

Impulse-Noise and Blast-Wave Effects

Impulse noise occurs with shooting or in industry, see table 5. Here it is particularly noteworthy that overpressures produced by toy weapons or firecrackers are in the same range as those of real rifles or those experienced by artillery gun crews. The durations and thus pulse energies may differ, though.

In explosions, overpressures can reach many times the normal atmospheric pressure. The pressure time course is usually that of a strong-shock wave, i.e., a fast increase and then a slower, more or less linear decrease via a negative phase to ambient pressure. However, whenever there are walls, reverberations will occur, increasing the duration and energy to which the ear is exposed.

Table 5: Peak pressure values of several sources of impulse noise, measured at (potential) ear positions (of worker, marksman or gun crew). Note that normal atmospheric pressure is 101 kPa.

Source	Peak overpressure / kPa	Peak level/ dB
Drop forge	0.11	135
Shooting bolts into walls, 80 cm	0.63	150
8 toy pistol types, 50 cm	0.63-2.0	150-160
3 toy paper-cap gun types, 30 cm	0.89	153
8 firecracker types, 3 m	0.063-63	130-190
Sonic boom low-flying aircraft (N wave)	2.4-6.9	162-171
Pistol	5.0	168
Rifle	1.7	159
4 rifles	1.78-8.43	159-173
Automatic rifle	7.2	171
Field cannon 105	50.3	188.0
17 Pdr. T/A gun	54	188.6
3 inch mortar short	58	189.2

Auditory Effects of Impulse Noise

Exposure to impulse noise causes similar effects as continuous noise: at lower levels there is a TTS, first at 4-6 kHz. For repeated exposure over long time, this may develop into PTS and deteriorate by involving a wider frequency band. At higher levels, permanent damage may ensue even from one or a few events. With impulses the individual susceptibility varies even more than with continuous noise. This is demonstrated in the first entries of table 6 which shows TTS and PTS data from humans. Ear pain may occur already at

0.36 kPa overpressure (145 dB), however, there are cases of no pain even when both eardrums were ruptured. Table 7 gives results from animal experiments. With impulse noise, TTS often increased in the first hours after exposure.

Table 6: Auditory effects of impulse noise and blast waves on humans.

Peak level / dB	Pulse duration	Number of pulses	TTS	PTS	Remarks
140	2 ms	75	40 dB at 4 kHz	none	most sensitive subject
155	2 ms	75	< 40 dB at 4 kHz	none	least sensitive subject
159	rifle shots		30 - 80, recovery in up to 6 days	none	marksman position
189	gun shots		30 - 80, recovery in up to 6 days	none	gun-crew position
180-183	blank shot		30 - 80, recovery in up to 6 days	none	ear near rifle muzzle
186-189	3" mortar	first shot	max. 75 dB at 5.8 kHz		monaural exposure - pain, tinnitus
		second shot after 80 min.	recovery up to 5.8 kHz in 2 months	50 dB at 8.2 and 9.7 kHz	eardrum rupture, bleeding
Fire-cracker 0.5 m from ear		1		60-80 dB at ≥ 3 kHz	male student
150-160 at 0.5 m	toy weapons		with 2 - 5 % of population (600)	with 2.5 % of population, mean 29 dB at 4 kHz	village festival in India
130-190 at 3 m	firecrackers		with 2 - 5 % of population (600)	with 2.5 % of population, mean 29 dB at 4 kHz	village festival in India
162-171	40-400 ms	many		none	sonic-boom N waves

Table 7: TTS, PTS, and physiological damage produced by impulse noise in animals

Animal	Peak level / dB	Number of pulses	Pulse duration	TTS	PTS	Physiological damage
Rhesus monkey	168	2	60 μ s pos., 100 ms neg. press.	33 dB median at 14 kHz	some	
		10 - 20 more			up to 15 dB median	local or extended loss of hair cells
Chinchilla	131, 135, 139, 147	1, 10, 100	~ 5 ms (reverberant)	15 - 90 dB mean	0-45 dB mean	hair cell losses roughly parallel to PTS
Guinea pig	153	500	35 μ s pos. press. (toy cap gun)			local hair cell damage as from 125-130 dB of 2 kHz for 4 h

When considering safe exposures to impulse noise, the peak level, duration, spectral content, pause interval, and number of impulses have to be taken into account. As a criterion for short impulses, a peak level of 162 dB (2.5 kPa) has been given.[66]

Concerning higher overpressures from explosions, experiences exist with humans who suffered from war, bombings, and, rarely, industry accidents; experiments have been done on preparations from human cadavers and with animals. The overpressure threshold for eardrum rupture has been given as 35 kPa (peak level 185 dB) (table 8). Only at shorter durations will the inertia of the eardrum and middle ear play a role to withstand higher pressures.

Among the victims of bomb blasts there is a high incidence of eardrum rupture. Fracture or displacement of the middle-ear ossicles is rare. Hearing loss, pain, tinnitus, and vertigo are the most common symptoms; the latter may often have to do with direct head injury. Smaller eardrum ruptures heal to a large extent. The other symptoms usually decrease over time as well, but often a permanent hearing loss remains.

In animals, eardrum rupture from blasts has been studied for decades, using atmospheric nuclear explosions, shock tubes, or live ammunition. Peak

overpressures for dogs, sheep, pigs, and monkeys are similar to those of humans.

Table 8: Severe damage to humans by strong-shock waves, e.g., from blasts (fast pressure rise, then about linear decrease with the duration given). For each effect, three pressures are shown: the threshold below which the effect will not occur, the level where the damage is expected to affect 50% of the exposed persons, and the 100% level. The pressures are the peak effective overpressures (free-field if parallel, free-field plus dynamic if perpendicular incidence, and reflected if in front of a large surface). Due to variability and - in the case of humans - non-availability of experiments, ranges are given instead of fixed values. For repeated exposure, damage thresholds are lower. For shorter durations, thresholds are higher. Note that normal atmospheric pressure is 101 kPa corresponding to 194 dB peak level.

Damage	Threshold overpressure / kPa	Overpressure for 50 % incidence / kPa	Overpressure for 100 % incidence / kPa
Eardrum rupture			
fast rising, duration 3 and 400 ms	35	105	
slowly rising/static	42-55	~150	
Lung rupture		"severe"	"severe"
duration 3 ms	260-340	680	680
duration 400 ms	83-103	260	260
Death			
duration 3 ms	770-1100	1100-1500	1500-2100
duration 400 ms	260-360	360-500	500-690

Non-Auditory Effects of Impulse Noise

Vestibular effects of impulse noise were observed with humans as well as with animals. Guinea pigs exposed to rifle shots showed not only severe damage in the cochlear organ of Corti, but also lesions in the vestibular end organs, even though the animals had not shown marked signs of vestibular disturbance. With soldiers suffering from hearing loss due to exposure to firearms as well as with bomb victims, vestibular damage was found. There are, however, several ways of compensating for a loss of vestibular-organ sensitivity.

The organ second most sensitive to blast is the lung with the upper respiratory tract. As a marker for the threshold of unsafe levels, the occurrence of

petechiae (bleeding from very small lesions of capillaries, harmless and self-healing) in the respiratory tract has been proposed; these occur at tens of kilopascals (about 180 dB peak level). With higher pressures, however, large hemorrhages form not only in the tracheae, but also in the lung, due to contusion. Tissue tears may lead to large-scale bleeding or edema in the lung and to air emboli which eventually can cause death by suffocation or obstruction of blood vessels. With sheep exposed to shock waves between 86 and 159 kPa (193-198 dB) and about 5 ms duration, lung injury ranged from moderate to strong, but still sub-lethal. Estimates of overpressures for human lung damage and death are given in table 8.[67]

Table 9: Simplified summary of the threshold sound levels in dB for various effects relevant for acoustic weapons in the different frequency ranges (rms levels) and for blast waves (peak levels). Note that the levels are approximate, that the effects change smoothly with frequency and depend on duration, and that there is wide invidual variability. For details, see the respective subsections in the text and the references given there. k: kilo (1000).

Range	Frequency / Hz	Ear pain	PTS from short exposure	Eardrum rupture	Transient vestibular effects	Respiratory organs
Infrasound	1 - 20	160 .. 140 (1 .. 20 Hz)	none up to 170	>170	none up to 170	none up to 170
Low audio	20 - 250	135 - 140	none up to 150	160	150 mild nausea	150 intolerable sensations
High audio	250 - 8 k	140	120 .. 135 .. 150 1 h .. 7 min .. 0.4 s strongest at 1-4 kHz	160	140 slight equilibrium disturbance	140 tickling in mouth etc. 160 heating
Very high audio/ ultrasound	8 k - 20 k/ > 20 k	140	none up to 156	?	none up to 154	140 tickling in mouth etc. 160 heating
Blast wave	-	145	150 - 160	185	160	200 lung rupture 210 death

Production of Strong Sound

Whereas sources of audio sound are well known, this is much less so for sources of low-frequency sound, and in particular of infrasound, which occurs at surprisingly high levels in everyday life. Thus several low-frequency sources are described first. Then, strong sources potentially usable for weapons are discussed.

Sources of Low-Frequency Sound

Infrasound proper is produced naturally by sea waves, avalanches, wind turbulence in mountains, volcanic eruptions, earthquakes, etc. Whereas such waves are only very slightly absorbed and - augmented by high reflection at the ground and a refracting channel in the atmosphere - can travel thousands of kilometers, the pressures and frequencies are such that humans do not hear them, and all the more are not negatively affected. Thunder has time-varying spectral peaks from infrasound to low-audio sound and can of course be heard. Wind gusts can produce quite high dynamic pressures; from the expression for the dynamic pressure

$$p_d = \infty_0 v^2 \surd 2 \tag{3}$$

(the air density at sea level is ∞_0=1.2 kg/m^3), it follows that for a peak wind speed of v=10 m/s the peak pressure is 65 Pa, corresponding to a level of 130 dB; with gale speed of 40 m/s, 1.04 kPa or 154 dB results. That such pressure fluctuations do not produce pain is due to the fact that wind varies on a time scale of seconds, i.e., with frequencies below or about 1 Hz.
Human-produced infrasound can have comparable or even higher amplitudes. Diving into water of density ∞_W to a depth of $\varnothing h$=2 m increases the pressure according to

$$\varnothing \infty = \infty_W \, g \, \varnothing h \tag{4}$$

(g=9.81 m/s^2 is the gravity acceleration at sea level) by $\varnothing p$=19.6 kPa (level 180 dB) within a second or so.[68] Blowing into another's ear can produce 170 dB. Even running produces considerable amplitudes; applying (4) with an rms head motion amplitude of $\varnothing h$=0.1 m and the density of air ∞_0 results in 1.3 Pa (level 96 dB).

Whereas these examples have dominant frequencies around or below 1 Hz, sounds from jet aircraft, rockets or airbag inflation reach up to and into the audio range.

Lower levels are produced by wind turbines, air conditioning and ventilation, and inside cars or trucks; opening a window produces a marked increase in the infrasound region. In industry, low-frequency sound is produced by compressors, crushers, furnaces etc. In the engine room of ships, high levels have been found.

Finally, blast waves need to be mentioned. Their overpressure amplitude can be arbitrarily high, whereas the following negative wave is of course limited to the negative atmospheric pressure (101 kPa at sea level).[69]

In order to test effects of low-frequency sound, special test equipment has been developed. For testing only the ears, low-frequency 15-W 30-cm loudspeakers have been tightly fitted with a plate; a hole connected this to the ear defender of a headset. Thus, levels up to 140 dB (400 Pa) were achieved.[70]

In order to test whole-body exposure, several test chambers of 1-2 m^3 volume have been built. Here also sealing is necessary to prevent pressure equalization with the outside at wave-lengths larger than the chamber dimension. One chamber working with six 0.46-m loudspeakers achieved 140 dB (200 Pa).[71] However, speakers provide only limited travel (1 cm or less) of their membranes. Stronger pressure variation is possible with pistons driven, e.g., hydraulically. For example, the Dynamic Pressure Chamber built at the Wright-Patterson Air Force Base in Ohio, U.S., has one piston of 0.46 and another of 1.83 m diameter and 12 cm maximum travel; this can achieve pressure levels of 172 dB (8.0 kPa) from 0.5 to 10 Hz, falling to 158 dB (1.6 kPa) at 30 Hz.[72] Note that the same piston, when working into free air at 10 Hz, is equivalent to a spherical source of only 82 Pa rms pressure (132 dB) at 1 m radius; at 1 Hz, 0.82 Pa (92 dB) would remain, with 6 dB decrease per doubling of distance.[73] This demonstrates the difficulty of producing low-frequency sound of high intensity in free air, and shows why tight closure of the test chambers is required.

Table 10 lists several sources of low-frequency sound.

Table 10: Sources of low-frequency sound, dominant frequency range, and sound pressure level at typical distance (o.c.: own calculations).

Source	Dominant frequency range / Hz	Sound pressure level / dB	Ref.
Geophysical	< 0.01-10	54 - 104	74
Thunder at 1 km	< 4 - 125	< 114	75
Wind fluctuations	~ 1	up to > 160	o.c.
Running	< 2	95	76
Blowing into another's ear	~ 0.5	170	76
Diving to 2 m of water	~ 1	180	76
Wind turbine, 150 m downwind	2 - 10	80	77
Ventilation/air conditioning	1 - 20	60 - 90	77
Industry	5 - 100	70 - 110	78
In car (window closed)	5 - 100	100	78
In car (window open)	1 - 30	120	78
Jet aircraft (underneath flight path at airport)	10 - sev. 1000	135	79
Jet engine with afterburner (at runway margin)	20 - 800	148	80
Large rocket, crew compartment	10 - 2000	135	81
Large rocket at 1.6 km	1 - 200	130	82
Sonic booms	1 - 100	120 - 160	83
Airbag inflation	~ 5 / 500 - 1000	170	84
Ship engine room		133	85
Blast wave	< 1 - 100	unlimited	
Loudspeaker headset	1 - 200	146	70
Whole-body chamber, loudspeakers	2 - 100	140	71
Whole-body chamber, piston	0.5 - 10/30	172/158	72

Acoustic Sources Potentially Usable for Weapons

Strong sounds can of course be produced by *loudspeakers* connected to amplifiers.[86] Providing enough electrical power requires a generator or heavy batteries, and achieving very high levels outdoors needs very large banks of speakers. Typical maximum electrical powers fed to one speaker are a few 100 W, of which only 1 or 2 per cent are converted to acoustic power, due to the membrane-air impedance mismatch.[87] Better efficiencies (10 to 50 %) are possible with (exponential or other) horns in front of the speaker which also improve directivity. For low frequency, horns have to be large.[88]

The main advantage of loudspeakers, namely their capability to emit a broad range of frequencies without large distortion, may not be needed for acoustical weapons, however. If just loud noise is to be produced, there are simpler possibilities, e.g., a siren or a whistle. Table 11 lists such sources with their properties.

In a *siren*, an air flow is periodically opened and blocked by a rotor the holes of which pass holes in a stator. Whereas early types had efficiencies of 1 - 2 per cent, already in 1941 a model was built which produced about 37 kW acoustical power (at 460 Hz) from 52 kW air flow power, i.e., with about 70% efficiency. This device - with its 71 kW and 15 kW combustion engines for the compressor and rotor, respectively - was mounted on a small truck; the six exponential horns of combined diameter 0.71 m provided a direction pattern with half-pressure angle of about 40° from the axis, about fitting to diffraction of the 0.75-m wavelength. With pressure levels above 170 dB in the horns, the wooden horns used first were destroyed during the first 5-minute test and had to be replaced by ones made of steel. With propagation in open terrain and a 1.42 m wide extension horn, an approximate $1/r$ decrease of the maximum pressure – due to spherical propagation – was observed to more than 500 m distance; on-axis levels were 137 dB, about the pain threshold for the unprotected ear, at 30 m and 127 dB at 100 m.[89]

Whereas somewhat more compact siren designs at the same power level are certainly possible, the input power required, the limits on flow and pressure within the siren and the size of the horns for impedance matching and achieving directivity for frequencies up to hundreds of Hertz result in sizes of 1 meter and more – the larger, the deeper the frequency. The device will require at least a pickup truck for mobility.

Sirens can also be used to produce high-frequency sound, up to the ultrasonic region. For example, with a device of 0.3 m size and 25 kg mass (without compressor) working with 200 kPa overpressure and an air flow of 0.1 m^3/s, levels of 160-165 dB with more than 2 kW of acoustic power were produced at

3 to 20 kHz, at an efficiency of 20%.[90] Another device produced about 160 dB at low ultrasonic frequencies and more than 140 dB at 150 kHz; higher levels were possible in the audio range.[91]

The siren principle – modulation of an air flow by opening and closing of holes – can also be used to produce sound of arbitrary waveforms. One example of such an infrasound-capable siren speaker is the Mobile Acoustic Source System (MOAS) which the National Center for Physical Acoustics at the University of Mississippi built for the Battlefield Environment Directorate of the U.S. Army Research Laboratory.[92] This unique system can provide 20 kW of acoustic power through an exponential horn of 17 m length and 2.3 m maximum diameter; the cutoff frequency is 10 Hz. It is mounted together with the 115 kW Diesel compressor on a telescoping semi-trailor. Here, a cylinder with slits on the circumference is moved electrodynamically past corresponding slits on a fixed cylinder, thus the air stream can be modulated by the current in the driving voice coil. From 63 to 500 Hz the on-axis frequency response is essentially flat, about 152 dB at 1 m radius for an equivalent point source; below, it falls to about 130 dB at 1 m at 10 Hz. From the first number, one can compute that the on-axis level decreases below 137 dB, about the pain threshold for unprotected ears, at 5.6 m from the assumed point source (located in the centre of the horn opening), i.e., already in the immediate vicinity.[93] The 120 dB range is 40 m. For infrasound, the increasing pain threshold and decreasing horn efficiency combine to prevent ear pain even close to the mouth, again demonstrating the difficulty of producing very high low-frequency amplitudes in free air. The main purpose of the MOAS is to test atmospheric propagation over many kilometers; another one is to simulate vehicle noise. The strong non-linearity in the device does not hamper these applications.

Periodic strong low-frequency air vibration can also be produced aerodynamically, by non-linear production of turbulence interacting with resonators, as in organ pipes and *whistles.* In the Galton whistle an air flow from an annular orifice hits a sharp circular edge inside of which is a cylindrical resonating volume. This whistle type has been used to produce frequencies from infrasound to ultrasound, mainly depending on the resonator size. Some variation of resonance frequency is possible by adjusting the length of the cavity. In the region 40 to 200 Hz, other whistle types have produced higher acoustic powers, up to the kilowatts range, with sizes on the order of 1 meter.[94] Infrasound would require much larger resonators (frequency scales inversely with resonator length) and compressor powers (scaling with air flow area).

For high audio frequencies and ultrasound, Galton whistles are less powerful than Hartmann whistles, where the annular orifice is replaced by an

open nozzle. These produce frequencies from several kHz to about 120 kHz; modified versions have achieved up to about 2 kW at 4 to 8 kHz at efficiencies of up to 30%. Using a parabolic reflector of 200 mm diameter, a beam width (full width at half maximum pressure) of about 30° was achieved. For ultrasound, using multi-whistles up to 600 W were achieved with about 10 and 33 kHz.[95]

In order to produce high-power ultrasound in air, *piezoelectric transducers* vibrating larger disks can be used. With one design, a stepped-thickness disk to achieve in-phase emission despite nodal circles, sound levels above 160 dB (2 kPa) were reached in front of the 20 cm diameter disk; it had to be water-cooled to avoid breaking. The efficiency was about 80%, the sound power up to about 200 W. The resonance bandwidth was only a few Hz. The half-intensity beam width was 5° (about fitting to linear diffraction), and the on-axis level had decreased to 150 dB (0.63 kPa) at 1 m distance.[96] Thus, at 10 m 130 dB (63 Pa) would result in the case of linear propagation, with an additional attenuation by 8 dB (factor 0.4 in pressure) due to absorption. However, shock would set in at about 0.1 m, increasing the losses.[97] In an experiment, with a level at the source of 153 dB (0.89 kPa) only about 123 dB (28 Pa) remained at 5.7 m distance.[98]

Finally, there is the possibility to produce a shock pulse by an *explosive blast.* In the case of spherical propagation even a sizable charge of 1 kg TNT may produce ear pain to about 200 m, whereas injury or fatality is expected only to a few meters.[99] The latter use would of course represent a traditional weapon and damage mechanism (note that in many weapons the lethality radius against persons is increased beyond the one due to blast by packing shrapnel around the explosive). Utilizing the ear pain mechanism with a spherically expanding shock would be problematic for several reasons. With regard to the effect, because the user needs to be protected, which is done best by distance, the charge is usually thrown before it is ignited. Since each charge would produce just one pulse, it could be necessary to repeat the use often. Seen from a viewpoint of humanitarian law or of non-lethality, on the other hand, there is the danger that the aiming is not exact and the charge explodes too close to someone, causing permanent injury or death. There may be an exception with very small charges, which could be used to cause surprise and confusion, especially within closed rooms. But here the visual effects of the accompanying light flash may even be more important, and such weapons are already in use. With very small charges (grams to tens of grams), there is also the principal possibility of a rifle-like weapon shooting explosive bullets to some distance (see below). If the explosion does not occur in free air, but in some open cavity or tube, resonance can intensify a certain frequency range.

A new perspective on shock-wave weapons would exist if it were possible to direct the shock, avoiding spherical distribution of the energy released, and so having only to deal with, e.g., 1/r decrease with distance – due to shock heating of the air – in the theoretical case of a beam of constant width. In the absence of published data, some speculation is justified for a preliminary analysis. Conceivably, the spherically expanding shock wave from an explosion could be caught in surrounding tubes, the other ends of which would be bundled in parallel in a circular, approximately planar transmitting area. By suitable bends, the tube lengths would vary in such a way that the individual shock waves would arrive about simultaneously at the openings, there combining to a common large shock wave which would start with an approximately planar front. This would be equivalent to a homogeneous layer of explosive on the emitting area ignited nearly simultaneously everywhere. The explosive layer could of course also be formed by, e.g., gasoline mixed with air, sprayed from small nozzles, ignited by an array of spark plugs. The main question here is how far the beam radius would remain the same, or how soon spherical spreading – with the accompanying shock $1/r^3$ decrease with distance – would set in. However, strong shock waves expanding into free air suffer from diffraction from the beginning, even though modified by the pressure dependence of speed.[100] Thus, it seems that although some concentration of the energy into a cone may be possible, spherical propagation will hold from a distance several times the source diameter. More definite statements require a detailed study.

One can also speculate what would happen if such explosions - with initially planar, bounded wave fronts – were produced repeatedly. In analogy with combustion engines, where many thousands of ignitions can occur per minute in each cylinder, frequencies of 100 Hz are conceivable with liquid fuel, with micromechanical valves etc. potentially much higher values. Of course, cooling, withstanding the overpressure pulse, and the recoil will present formidable, but solvable, engineering problems. Estimates show that megawatt power,[101] source levels around 180 dB (tens of kPa pressure, still marginally in the weak-shock region with nearly symmetric waveforms) are possible with a fuel consumption of tens of grams per second, comparable to a tank engine.[102]

After the first shock, each sufficient one would propagate in already heated gas with a correspondingly higher speed. Thus, later shocks would continuously reach and replenish the first front. As there would be some decrease of pressure and temperature away from the beam axis, following wave fronts would become more forward-dented and would suffer more from diffraction loss away from the axis. Quantitative estimates of the overpressure decrease

with the distance and angle from the axis require much more clarification by the developers of such systems and/or a detailed theoretical study.[103]

In order to overcome the amplitude decrease with distance, one can also use a *small source* which is moved close to the target. The principle is exemplified by exploding or whistling firecrackers. The latter could contain a whistle or siren, driven by a pressurized-gas container or a gas generator (as, e.g., in an airbag), and could work for many tens of seconds up to minutes, depending on size.

With a mass of hundreds of grams, both types could be thrown by hand or shot by a rifle; heavier "sound grenades" could be shot by a larger (air) gun.[104]

Table 11: Strong sound sources potentially usable for acoustic weapons. The values given are typical or apply to a specific device (notional for the hypothetical repetitive-blast device). k: kilo (1000); o.c.: own calculations. Note that in case of very high levels close to the source, at high audible or ultrasound frequencies non-linear effects will lead to strong absorption and fast decrease of pressure level with distance.

Source	Diameter of emitting area / m	Frequency / Hz	Acoustic Power / kW	Sound pressure level / dB	At distance / m	Ref.
Large siren	1.4	200 - 600	37	137	30	89
Small siren	0.3	3 k -20 k	2	165	close	90 91
Large air-flow-modulation speaker	2.3	10 - 500	20	126	27	92
Giant whistle	0.2	40 - 200	several	160	close	94
Hartmann whistle	0.2	4 k - 8 k 20 k	2 0.6	160	close	95
Piezoelectric transducer with disk	0.2	20 k	0.2	160	close	96 98
Explosive blast	1	< 1 - 100	unlimited	unlimited		
Hypothetical repetitive blast	1	100	1000	180	close	o.c.

In conclusion, it is possible to construct strong sources of low-frequency sound which can be tuned to some extent, or which can deliver arbitrary waveforms, with efficiencies between 10% and 70%. Beam widening roughly corresponds to diffraction. Resonators, air flow limits, horns for directivity, and power requirements, all drive the size of such sources with their auxiliary equipment into the range of 1 meter and more, and the mass to several hundred kilograms and more.

Higher audio-frequency and ultrasound sources could be somewhat

smaller, but due to their power requirements no great reduction of the total system size seems possible. (Compare the sizes of the required engines, electrical generators or compressors with those of commercial gasoline-engine AC generators of 1 to 5 kW.)

Explosive-driven sources can produce blast waves, probably also with repetition at low audio frequencies. Megawatt powers seem achievable, again with source sizes on the order of 1 meter.

Hand-held acoustic weapons of pistol or rifle size with ranges of tens of meters can be excluded almost certainly. The only exception would be a small whistling or exploding "sound grenade" thrown or shot to within a few meters from a target.

Protection from High-Intensity Sound

The sound pressure acting on the eardrum can be reduced by earplugs which are inserted into the external ear canal, or by ear muffs enclosing the outer ear. Whereas both types can provide attenuation from 15 to 45 dB at higher frequencies (500 Hz and above, including ultrasound), earmuffs are less efficient at low frequencies (250 Hz and below); at some infrasound frequencies, they even may amplify levels. Here, earplugs are better; those of the premolded or user-formable type attenuate by 10 to 30 dB at low frequencies. The best low-frequency protection is provided by earplugs made of slow-recovery, closed-cell foam; these can reach 35 dB if inserted deeply. Combinations of earplugs and earmuffs are advisable for protection against impulsive peak sound levels of 160 dB and above. Combining an earphone with a sound-absorbing helmet can achieve 30-50 dB attenuation from 0.8 to 7 kHz. Much stronger attenuation at the external ear is not useful because sound reaches the inner ear also by bone and tissue conduction.[105]

Protection against whole-body exposure can principally be provided by enclosures that are sufficiently stiff so that they are not easily vibrationally excited transmitting sound to the inside, or by linings with sound-absorbing, e.g., porous material. For jet engine technicians, protective suits exist.[106] The absorption mechanism loses its value with low frequencies, however – when the lining becomes thinner than about one-fourth wavelength (e.g., 0.34 m for 250 Hz), the absorption decreases with decreasing frequency.[107] For very high impinging levels at high frequencies, heating in the absorptive material may present a problem, but in the present context this is mostly theoretical because of the strong decrease with distance.

An armored vehicle, if completely closed, should provide considerable pro-

tection against low-frequency sound. A normal road vehicle, on the other hand, is neither air-tight nor are windows or panels stiff enough not to transmit impinging low-frequency pressure variations. Similarly, low-frequency sound may enter buildings via slits or closed windows. If the frequency corresponds to a room resonance,[108] internal pressures by far exceeding the impinging ones can develop. Utilizing this effect requires a variable-frequency source and some on-site modelling and/or experimentation. It is conceivable that during resonance build-up windows burst – due to their large areas at levels below the human pain threshold – diminishing the resonance effect again.

At higher frequencies, on the other hand, walls, windows, sheet metal and the like can provide substantial attenuation.

Therapy of Acoustic and Blast Trauma

Here only a few indications will be given.[109] Some immediate effects of overexposure to sound may simply vanish with time – from minutes to months – such as hearing loss, tinnitus, pain, or vertigo. Some, however, may remain permanently. These are probably caused by inner-ear damage, e.g., to hair cells on the basilar membrane in the cochlea, or by similar effects in the vestibular system. Such damage seems to grow for a few hours after acoustic trauma, which may have to do with reduced blood supply. Thus, drugs furthering blood circulation are often given. There are conflicting studies on the success of such treatment.[110]

Since further exposure to strong noise increases the damage and interferes with a healing process, achieving quiet at an injured ear as fast as possible (e.g., by an earplug) is an important part of therapy.[111]

Tympanic-membrane ruptures produced by bombings healed spontaneously in 80-90% of the cases. Operations closing the membrane are mainly required when the perforations are larger than one third. Fracture or displacement of middle-ear ossicles occur more rarely and indicate much more severe blast damage; these require much more complicated surgery.[112]

Whereas there are cases when nearly full recovery of hearing occurred even after ruptures of both eardrums, it is more likely that PTS - of moderate to severe extent – ensues.[113] Therapy cannot do much about that; providing hearing aids may be the main form of help after the fact. In case of near-deafness, providing a cochlear or even brain-stem implant for direct electrical stimulation of sensory or nerve cells - an expensive treatment – may restore significant hearing and speech-perception abilities.[114] Prevention, e.g., by ear

protection, is the only reliable way to avoid permanent hearing losses.[115]

Conclusions

Judging acoustic weapons is particularly complicated because there are so many facets. The potential effects range from mere annoyance via temporary worsening of hearing to physiological damage of the ear, and in the extreme even of other organs, up to death. The criteria will also differ according to the intended context and scenario of use; the spectrum extends from close-range protection of fixed installations to mobile systems, on the one hand for law enforcement, on the other hand for armed conflict. Lack of official information on development projects and unfounded allegations on properties and effects of acoustic weapons make judgement even more difficult.

Rather than trying to provide a complete judgement for all possible weapons types and use options, this article aims at providing facts that further the debate and eventually help to arrive at responsible decisions on how to deal with acoustic weapons. This section summarizes the main results of the study, and ends with a few general remarks.

Effects on Humans

Contrary to several articles in the defence press, high-power infrasound has no profound effect on humans. The pain threshold is higher than in the audio range, and there is no hard evidence for the alleged effects on inner organs, on the vestibular system, for vomiting, or uncontrolled defecation up to levels of 170 dB or more.

Throughout the audio region (20-20,000 Hz), annoyance can occur already at levels far below bodily discomfort, in particular if the sounds are disliked and/or continue for a long time. This may produce the intended effects in specific situations, e.g., a siege of a building occupied by criminals. Because usually no lasting damage would result, there is no reason for concern under humanitarian aspects.

The situation changes at higher levels, where discomfort starts at about 120 dB and pain in the ears occurs above about 140 dB. As a consequence of intense sound, at first a reversible deterioration of hearing occurs (temporary threshold shift). Depending on level, duration, frequency, and individual susceptibility, however, already short exposures at levels above, say, 135 dB can produce lasting damage of hearing (permanent threshold shift). Such damage need not be sensed immediately by the victim; the deterioration may become

known only later. It is mainly located in the inner ear. The eardrum ruptures at about 160 dB; even though it may heal, permanent hearing loss may remain.

With low audio frequencies (50-100 Hz), intolerable sensations mainly in the chest can be produced – even with the ears protected – but need 150 dB and more.

At medium to high audio frequencies, some disturbance of the equilibrium is possible above about 140 dB for unprotected ears. At even higher levels, tickling sensations and heating may occur in air-filled cavities, e.g., of the nose and mouth.

High audio frequencies (above 10 kHz) produce less threshold shift, and at ultrasound the ear is essentially untouched if levels are below 140 dB. In these frequency ranges heating of air cavities, of textiles or hair may become important above about 160 dB.

Early therapy may lead to some improvement after acoustic trauma. However, permanent hearing loss, once occurred, cannot really be reversed, leaving hearing aids and cochlear implants as the main means of reducing the consequences.

Shock waves from explosive blasts – for which the name "acoustic" is questionable – can have various effects. At moderately high levels (up to about 140 dB), there is temporary hearing loss, which can turn into permanent one at higher values. Above 185 dB eardrums begin to rupture. At even higher levels (about 200 dB, overpressure already 3 times the atmospheric pressure), lungs begin to rupture, and above about 210 dB some deaths will occur.

Potential Sources of Strong Sound

Loudspeakers are not very efficient in producing strong sound, unless coupled with horns. Higher levels are more easily achieved with sirens producing single tones of variable frequency, powered, e.g., by combustion engines. At low frequencies sound powers of tens of kilowatts with a source level of 170 dB have been achieved; in the high audio and ultrasound range the figure is a few kilowatts at 160 dB. With a siren-type speaker low-frequency sound of arbitrary waveform can be produced at similar powers and pressure levels. With whistles, again mostly tonal sound is produced; at low frequencies, tens of kilowatts should be possible, at high audio frequencies several kilowatts, and in the ultrasound region around 1 kilowatt.

Explosive charges produce a blast wave the overpressure of which (at constant distance) scales linearly with the energy released; thus there is practically no upper limit at close range. A new type of source would result if

explosions do not occur one at a time, but in fast sequence, with frequencies, e.g., in the low audio range. Here, megawatt acoustic power and 180 dB source level seem achievable in principle.

For nearly all source types mentioned, a typical size would be one meter or more. This holds for the source proper with its emitting area as well as for the associated power supply, e.g., a combustion engine. Rifle-like hand-hold acoustic weapons are only conceivable with ammunition for bangs or whistling; all other sources will be fixed, or will need a vehicle, helicopter or the like as a carrier.

Production of strong infrasound by non-linear superposition of two ultrasound beams is not realistic.

Propagation Problems

Whereas it is possible to achieve annoying, painful or injurious sound pressures for all source types mentioned – explosive blasts can even kill - if the target person is close to the source, there are great difficulties or unsurmountable problems when such levels are to be achieved at a distance.

The first obstacle is diffraction. Waves emitted from a source immediately diverge spherically if the wavelength is larger than the source; i.e., the power is spread over an area increasing with distance, and consequently the intensity and sound pressure decrease with distance. For source sizes on the order of one meter, this holds for frequencies below a few hundred Hertz. "Beams of infrasound" have no credibility. But even at higher frequencies with shorter wavelengths, where focusing or a beam of constant width can be achieved up to a certain distance, eventually spherical spreading will take over as well.

The second problem follows from the non-linear properties of the air. Whenever the sound pressure is as high as required for marked immediate effects, the wave crests move faster than the troughs, converting the wave into saw-tooth form after some distance. The ensuing shock fronts dissipate the wave energy much more strongly, so that the sound pressure decreases with the inverse of the distance, even for a plane wave without beam spreading, and more strongly in case of divergence. In the case of spherical blast waves, the decrease is by the cube of the inverse distance as long as the overpressure is larger than the normal atmospheric pressure.

Shock forms earlier and the associated energy losses become stronger with increasing frequency; thus, even if diffraction did not significantly reduce the sound pressure at a distance for some high enough frequency, shock-wave losses would then decrease the pressure from its initially high level along the beam. How far a given level can be projected depends on many details, such as

source size, frequency, the form of the starting wave front, humidity of the air, intended level at the target, but as a rule of thumb one can state that projecting really high levels (say, above 140 dB) to more than 50 m does not seem feasible with meter-size sources.

Only with single blast waves produced by sizeable explosive charges (above 0.1 kg TNT) can shock overpressures transcend such levels at such distances. Because for impulses the human tolerance is higher, and because of the steep decrease with distance, much higher overpressures with the capability for lung rupture and death would hold at closer range.

I am not aware of a plausible mechanism for an alleged "basketball-size acoustic bullet" that could be even lethal over several hundred meters; clarifying or reliably refuting this allegation needs further study.

The case is different if strong acoustic waves are set up indoors, where the power is kept in place by reverberation from the walls. Achieving high levels will be particularly effective at room resonances. Direct coupling – e.g., through ventilation ducts – would be most efficient; next could be application of sound pressure via closely fitting tubes pressed against windows. Radiating a sound from a distance would provide the worst coupling, but may suffice to set up resonance vibration under certain conditions.

Further Study

There are a few areas where clarification or more detailed scientific-technical studies would be helpful. The more important issues are:

- quantitative aspects of the propagation of bounded beams of shocked waves (weak and strong shock);
- the working principle and specifications of a possible multi-explosion blast wave source; and
- the possibility of "diffraction-free" propagation of high-power acoustic pulses over considerable distances ("acoustic bullets"), in particular using vortex rings.

General Remarks

As with other types of "non-lethal" weapons, with acoustic weapons there are the problems of dosage and susceptibility varying among individuals. Exposed to the same sound level, sensitive persons may suffer from permanent hearing loss whereas for others the threshold shift is just temporary.

Impressive effects on the sense of equilibrium or the respiratory tract occur only at sound levels which pose an immediate danger of permanent hearing damage. Therefore, the promise by acoustic-weapons proponents of "no lingering damage" could only be implemented by fairly drastic limits, say, a sound level of no more than 120 dB at anybody's ear. This, however, would forego many of the hoped-for effects of acoustic weapons.

Because protection of the ears can be quite efficient throughout all frequencies, it would certainly be used by armed forces, organized militias and bands, at least after the first experience with acoustic-weapons use by an opponent. But since protection is so simple and easily available, it would probably also soon be used by "normal" people in demonstrations, etc.

Considering aspects of international humanitarian law, a complete analysis needs yet to be done. At the present stage, a few preliminary thoughts seem justified.

Acoustic weapons are different from the recently banned blinding laser weapons in several respects:

- The argument that 80-90% of the human sensory input is provided by the eye can obviously not be transferred to the ear; thus an argument on unnecessary suffering cannot be made on a similar basis as with blinding weapons.[116]
- Physiological injury to the ear from blast is common with conventional weapons.
- Even with ruptured eardrums, healing or at least improvement of hearing is possible.
- Hearing aids and implants are available, whereas comparable aids for the visual system do not really exist.

Thus, the case for a preventive ban under aspects of the international law of warfare is much less clear-cut here than with blinding lasers.

On the other hand, acoustic weapons bear a larger danger of indiscriminate effects, even though only at shorter range. Several types of acoustic weapons would be difficult to direct at only one person, all the more at one part of a person's body, because diffraction produces wave spreading. Thus, in several conceivable situations non-combatants or by-standers would be affected. As long as effects are temporary, or permanent effects are slight, this may be acceptable in certain circumstances.

At fixed installations, even sound sources capable of afflicting considerable lasting damage at close range might not meet strong objections, since on

approach people would hear the sound and then feel pain and could in most situations withdraw voluntarily. However, if in a crowd pressing from behind, this may be impossible, so that one could demand non-damaging pressure levels (below, say, 120 dB) at the physical barrier protecting an installation.

Mobile acoustic weapons capable of producing permanent damage in a radius of, say, 10 or 20 m, would be much more problematic, especially in a law-enforcement context. One could probably not rely on the weapon users to keep certain limits; if to be obeyed at all, they would have to be built into the systems (e.g., in the form of absolute upper limits of power, or limits on actual power and duration depending on target distance, for targets within rooms special precautions would be needed).

The International Committee of the Red Cross has proposed four criteria for judging when design-dependent, foreseeable effects of weapons would constitute superfluous injury and unnecessary suffering. The first criterion is fulfilled if the weapon causes a "specific disease, specific abnormal physiological state, specific abnormal psychological state, specific and permanent disability or specific disfigurement."[117] Taken in this generality, certain acoustic weapons would fall under this rubric.

In sum, acoustic weapons would clearly not be the wonder weapons as sometimes advertised. Their use in armed conflict or for law enforcement would raise important issues concerning unnecessary suffering, protection of outsiders, and proportionality. One can conceive of special situations where acoustic weapons could add options for the application of legitimate force in a more humane way, possibly, e.g., in a hostage situation. However, the effects would be less dramatic than reported, especially on prepared opponents, whose own capability to inflict damage would not be reduced markedly. Thus the interest of armed forces and police in such weapons may turn out to be lower than their proponents would like.

This might mean that a determined attempt of the humanitarian-international-law community to preventively ban certain types of acoustic weapons may promise success. Because of the large variety of potential weapon types, of the effects on humans, and because of the large range of sound intensity potentially involved, for this purpose, clear definitions and criteria would be needed. One approach might, e.g., demand a limit of 120 dB at any publicly accessible point in the case of fixed strong sources. Mobile acoustic weapons could be banned – or limited to very low numbers for specific police uses – if they could produce more than, say, 130 dB at 5 m distance. Limits could also include the frequency-dependent human auditory sensitivity and be stricter in the range from 0.5 to 6 kHz. Such limits would aim at guaranteeing markedly less damage than usually afflicted with conventional fire weapons in armed

conflict; thus general acceptance could become a problem if the discussion were limited to the law of warfare proper.

A more general approach similar to the one taken for the ban on blinding laser weapons – banning weapons specifically designed to render people permanently deaf – seems less sensible here, since that is not the main goal of present acoustic-weapon development, and deafening at short range could readily occur as a collateral effect of weapons designed for producing only temporary effects at larger distance. An even more general ban on deafening as a method of warfare, is unrealistic in view of the multitude of blast weapons in the arsenals of armed forces.

Because of the ease of protection, it may turn out that armed conflict will be the least relevant scenario, and that other operations, e.g., for crowd control, will be more realistic. Thus, considerations on bans or limits should take law-enforcement and other uses of acoustic weapons into their view from the beginning.

These arguments show that detailed deliberations are needed in order to arrive at a sensible course of action. It is hoped that this article contributes to that debate.

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Appendix 1: Pressure Waves in Air[118]

Linear Acoustics[119]

In the air pressure variations produced at a source propagate as sound waves. The exact wave equation is non-linear; however, for small variations, e.g., sound pressure below about 0.001 times static pressure, i.e., below 100 Pa

(level < 134 dB), the pressure-volume curve of air can be replaced by its tangent and the equation linearized. In this case of linear acoustics, the sound speed is c_0=343 m/s at P_0=101 kPa static pressure and T_0=20 °C temperature, with density ∞_0=1.20 kg/m^3.

The sound pressure p is the deviation from the static pressure P_0. In order to estimate it for a simple source one can use the assumption of a monopole (i.e., a breathing sphere) emitting spherical waves in the open. If v_{rms} is the root-mean-square (rms) surface velocity of the sinusoidal vibration, the rms sound pressure – at distance r from the centre in the far field – becomes

$$p_{rms}(r)= \infty_0\ c_0\ k\ A\ v_{rms} \surd(4\neq r) \qquad \text{(A-1)}$$

where k=2$\neq/\infty$ is the wavenumber, ∞=c$_0/\infty$ the wavelength, ∞ the frequency. The rms intensity, i.e., the rms power per area transported with the wave, is

$$I_{rms}(r)= p^2{}_{rms}(r) \surd(\infty_0\ c_0) \qquad \text{(A-2)}$$

the product $Z_0=\infty_0 c_0$ is called the impedance of free air. The intensity decreases with $1/r^2$ since the rms pressure decreases with $1/r$. The total power P_{rms} emitted is the integral over the full sphere at r,

$$P_{rms}= 4\neq r^2 I_{rms}(r) \qquad \text{(A-3)}$$

which is constant absent other losses.

If the wave field is not spherically symmetric, but confined to some cone of solid angle $|$, the intensity in that cone will be higher by $4\neq / |$, and the pressure by the square root of that. If the source is a piston of radius a in an infinite, hard baffle, vibrating with rms velocity v_{rms} and frequency v, then the rms pressure at distance r and angle ∞ in the far field is

$$p_{rms}(r, \infty)= \frac{\infty_0 c_0}{4\neq r} k 2\, v_{rms} \neq a^2 \frac{2 J_1((ka)\sin\infty)}{(ka)\sin\infty} \qquad \text{(A-4)}$$

The Bessel function expression 2 $J_1(x)/x$ is close to 1 from x=0 to about $\neq/2$. Comparison with (A-1) shows that on the axis (∞=0) the sound pressure is twice the one from a simple spherical source of equal surface area or volume flow rate, the intensity is four times stronger, due to the reflection at the baffle, or the expansion into a half-space. If the baffle is removed and the piston conceived to move in the mouth of a pipe,[120] the factor 2, or 4 for intensity, would vanish, the pipe end would act on the axis like a simple source of equal area or volume flow rate.[121] When the wavelength ∞ is longer than 2 $\neq a$, the circumference of the piston, the argument of the Bessel function term is below

$\neq/2$ even for $\infty=\neq/2$, the second fraction in (A-4) is 1, i.e., the sound pressure is essentially the same in all directions, including along the baffle or even – if $\infty \geq 4\neq a$ backward for the case of the pipe. This means that in order to achieve directed emission for low frequencies, very large transmitting areas would be required, e.g., already for ∞=50 Hz (∞=6.8 m) a radius a clearly above 1.1 m is needed.

Transmitting a sound wave of sufficiently high frequency predominantly into a certain cone can be achieved by a horn with reflecting walls in front of the source, and enclosing the source at the back.[122] Due to its increasing cross section, it acts as an impedance transformer and can increase the efficiency of sound generation, e.g., from 1 - 2 % for a direct loudspeaker to 10 - 50 %.[123]
If parallel waves of constant intensity are emitted from a circular area, in the far field the innermost Fraunhofer diffraction spot is limited by the angle ∞_1 of the first null of the Bessel function in (A-4):

$$\sin\infty_1 = 1.22\infty\surd D \qquad \text{(A-5)}$$

where D is the diameter of the antenna. If the expression on the right is larger than 1, there is no null at all.

The intensity on the axis is

$$I_{max}(r) = P\neq D^2 \surd(4\infty^2 r^2) \qquad \text{(A-6)}$$

In the case of outdoors sound propagation, modifications apply due to several effects, most of which are small for the distances (10 to 100 m) considered here and are neglected for the simple estimates of the present assessment. However, some are difficult to assess in a given situation and thus add a significant amount of unpredictability for the use of acoustic weapons beyond about 50 m.

Non-Linear Acoustics - Weak-Shock Regime[124]

If the perturbations due to an acoustic wave are no longer very small compared to the static values, one has to consider the fact that the speed of propagation is no longer constant; it increases with pressure, density or particle velocity. Thus, regions of higher compression move faster, and regions of lower density more slowly, than the normal sound speed. This means that the wave form, even if sinusoidal at the start, becomes distorted (figure A.1 a). Relative to the zero crossings, the pressure peaks move forward and the troughs backward, finally forming a saw-tooth-like wave where at a given point in space there arrives first a positive pressure jump and then a linear decrease to the negative sound pressure minimum, repeated periodically (figure A.1 b). This

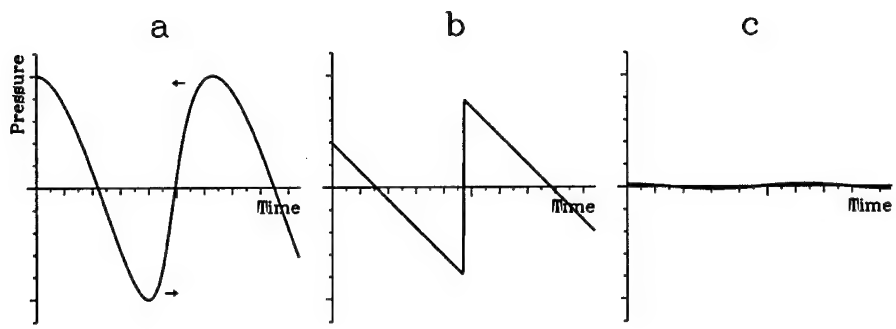

Figure A.1: Wave forms of an originally harmonic wave before and after shock formation. In the first stage (a), pressure peaks move faster and troughs more slowly, deforming the wave as it propagates. In the second stage, a rounded saw-tooth wave forms with strong dissipation in the shock front (b). The front becomes thicker and the amplitude weaker until finally a small sinusoidal wave remains (c). (Plotted vs. the space coordinate in propagation direction, the waves move to the right.)

can also be described as the successive build-up of harmonics of the original frequency (for an ideal saw-tooth wave, the amplitude of the n-th harmonic is proportional to $1/n$). Whereas dissipative losses in the medium are not important in the first build-up region, they increase strongly as soon as the shock front has been formed. During this second stage the amplitude and the non-linear distortion is slowly reduced, until the pressure becomes so low that linear propagation prevails again (figure A.1 c).

The details are complicated. For a plane wave, the rms sound pressure of a plane wave stays essentially constant during the first phase. After shock formation it decreases approximately as the inverse of the distance – note that this decrease holds for infinitely extended wavefronts and is not due to geometrical spreading. This phase ends with a low saturation amplitude which does not depend on the starting value. In the third phase, exponential attenuation prevails.

For spherical waves, the growth of the non-linear disturbance is accelerated in case of convergence, and decelerated for divergent waves, because the amplitude increases/decreases with radius r. If for a divergent wave shock occurs at all, the amplitude decrease is faster than with $1/r$; shock ceases at a

certain radius.

In case of bounded waves (beams), the amplitude at some distance depends on the relative contribution of non-linear versus diffraction effects. Quantitative statements require detailed studies.[125]

Non-Linear Acoustics – Production of Difference Frequency, Demodulation[126]

If two waves of different angular frequencies ∞_1, ∞_2 propagate in a non-linear medium, the superposition principle no longer holds and combination frequencies $n\infty_1+m\infty_2$ (*n*, *m* integer) are generally produced. In particular in the present case, the difference $| = \infty_1 - \infty_2$ of two about equal angular frequencies may be interesting, because the former, due to its low value, would be much less absorbed by the air than the latter ones. Also the beam widening by diffraction would be much lower.

Superposition of two waves of similar frequency at first produces a variation in amplitude with the frequency difference, similar to an amplitude-modulated wave. In case of plane waves, the modulation- or difference-frequency-wave amplitude $p_|$ will at first increase linearly with distance. After shock formation, however, it will saturate to a constant, with linear dependence on original amplitude p_0

$$p_| = \neq m | \; p_0 \vee (4\infty) \tag{A-7}$$

(m'' 1 is the degree of modulation). This holds for a triangular wave and is correct except a constant factor for an originally sinusoidal one too, analogously for the difference frequency. (A-7) means that the sound pressure of the low-frequency wave is always lower than the original wave starting pressure by a factor $| / \infty$, which is much smaller than unity under the assumptions made above.

Strong-Shock Regime[127]

In strong shock, as produced by an *explosive blast,* the overpressure is markedly above normal atmospheric pressure. A following underpressure pulse is limited to the atmospheric pressure, of course. Because of the high overpressure, the shock front moves with a velocity clearly above the sound speed. At any given distance, a fast overpressure jump occurs first, followed by a slower decrease to normal pressure, possibly via an under-pressure phase. After passage of the shock wave, the gas remains at elevated temperature and decreased density. The maximum overpressure scales approximately linearly

with the energy and for three-dimensional propagation decreases approximately with the inverse cube of the distance. As soon as the overpressure falls below atmospheric pressure, transition to weak-shock, and finally linear, propagation with the usual sound velocity, and inverse-distance times exponential amplitude decrease, takes place.

Figure A.2 shows several quantities for explosions of 0.1 and 1 kg TNT in free air at sea level. Figure A.2 a shows the shock overpressure. The transition from the r^{-3} (strong-shock) to the r^{-1} (weak-shock/linear-propagation) dependence is seen around a distance of 3 and 7 m, at overpressures around one-third the normal pressure. It is interesting that even with 1 kg, a considerable amount of explosive – maybe ten times of that in a hand grenade – the threshold for eardrum rupture (about 35 kPa, see 2.5) is crossed at less than 5 m. On the other hand, the peak level is higher than 145 dB (0.36 kPa) where most subjects had felt pain in laboratory experiments,[128] to about 200 m.

Figure A.2 b shows the duration of the positive-overpressure part of the shock wave. It is obvious that for small chemical explosions the pulse durations – at applicable distances – are on the order of milliseconds, thus in table 8 the damage thresholds for the short times apply.

For such short waves, the body is very quickly immersed in the same overpressure from all sides, and a sizeable net force is mainly exerted by the dynamic-pressure drag of the moving air behind the shock. Figure A.2 c shows the approximate dynamic impulse per area for unity drag coefficient.

A strong-shock wave suffers from diffraction as well, but with a modification in that the propagation speed depends on the local pressure. For an extended plane or spherical wave, this mechanism provides for some stabilization of the shock front: should a backward bulge develop at some part, confluence of the power there would accelerate that part again, and vice versa. However, shocks emanating from the open end of a tube show immediate widening and propagation even in the backward direction along the outer side of the tube.

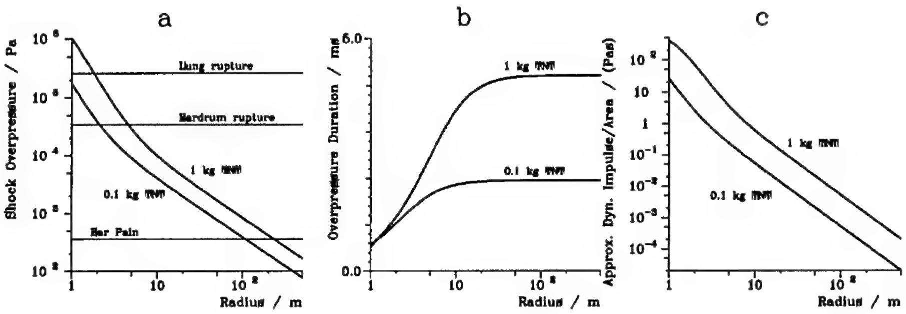

Figure A.2: Shock overpressure (a), overpressure-pulse duration (b), and approximate dynamic-pressure-caused impulse per area for unity drag coefficient (c), versus distance r for conventional explosions of 0.1 and 1 kg TNT at sea level in free air. The strong-shock regime with r^{-3} pressure decrease holds to about 2 and 5 m, respectively. For an explosion at hard ground the energy has to be multiplied by 2 or the distances by $2^{1/3}$=1.26. In (a), several damage thresholds are shown. Lung damage will occur below 0.8 m or 1.8 m, eardrum rupture is expected below 2 and 5 m, and some people will feel ear pain if closer than 100 m or 200 m, respectively. For distances above 1 m, the overpressure-pulse durations (b) are on the order of milliseconds. The drag-exerted impulse per area transferred to a small object can be gained from the approximate curves in (c) by multiplication with the drag coefficient.

For the present application the question is whether considerable shock energy can be focused into a narrow cone, avoiding distribution over a full sphere. Whereas shock overpressure would decrease in proportion to $1/r$ as long as the beam size would remain constant, the usual r^{-3} decrease would take over as soon as the size would increase. How far considerably stronger overpressure than for a spherical explosion would be possible needs a detailed study. However, it seems difficult to conceive of a shock wave from a 1-m source which is still bounded at, say, 50 m.

Appendix 2: Analysis of Specific Allegations with Respect to Acoustic Weapons[129]

The following sections deal with a few allegations made mostly in journalistic articles, first concerning weapons principles, then with respect to effects on humans.

Allegations Regarding Weapons Principles

Infrasound Beam from a Directed Source?

Several journalistic articles speak of an "infrasound beam" (see table 1). It is clear from the beginning (see equation (A-6)) that for long wavelengths a large emitting area will be needed to achieve substantial intensity at some distance.[130] In order to do a conservative estimate I assume a transmitter diameter of 3 m which is already fairly cumbersome, and the shortest wavelength compatible with the "infrasound" notion, namely ∞=17.2 m for a frequency of ∞=20 Hz at 340 m/s sound speed. For the acoustic power I take P=10 kW which might, e.g., stem from a combustion engine of 30-60 kW. The rms pressure at the source is then 0.77 kPa (level 152 dB). Because the wavelength is much larger than the emitter, the far-field intensity is the same in all directions; there can be no beam. Instead there is spherical expansion (as has been observed with the somewhat smaller MOAS device mentioned in the section on low-frequency sources).

Because of the large source and low frequency, no shock will form, and normal linear propagation with $1/r$ decrease of amplitude with radius will take place everywhere. At a notional distance of r=50 m the pressure will be 3.2 Pa (level 104 dB), several orders of magnitude below any appreciable effect of infrasound. Of course, should the sound wave, before leaving the emitting area, have passed through a much narrower duct with higher intensity, shock may have formed there, reducing the intensity outside even further.

Next, let us test the low-audio frequency of 100 Hz, the upper limit of where stronger non-auditory effects had been observed at about 150 dB level, and let us assume the same large emitter size of 3 m. In forward direction there is still spherical propagation without shock. The pressure at 50 m distance will be 16 Pa (level 118 dB), which is very loud but clearly below the pain threshold. Inner-organ effects as observed at about 150 dB will occur only immediately in front of the source. Aural pain and damage from short-term exposure is expected – in case of unprotected hearing – for distances up to a few meters.

At higher frequencies shorter wavelengths facilitate focused propagation. However, as a beam forms and becomes narrower, non-linear absorption becomes stronger in parallel. Whereas very high levels with drastic effects, e.g., on hearing or vestibular system, are possible at close distance, reaching the pain threshold at 50 m distance or beyond will be practically impossible.

Infrasound from Non-Linear Superposition of Two Directed Ultrasound Beams

One of the alleged early acoustic weapons (the "squawk box" mentioned in the

introduction) was said to utilize two near-ultrasound waves which would combine in the ear, producing an intolerable infrasound difference frequency (together with the ultrasound sum frequency).[131] In a short general analysis of acoustic weapons, the requirement of non-linearity for such production was mentioned explicitly. Here, the low-frequency component of, e.g., 7 Hz produced from 40.000 and 40.007 kHz was said to disturb the vestibular organ.[132] In neither case, however, was a quantitative estimate of the conversion efficiency made.

To analyze this allegation, one needs first to recall that in controlled experiments, infrasound of levels above 140 dB did not affect the vestibular system. Non-linear production of difference-frequency signals can occur either during propagation in the air or within the ear.[133]

First to conversion in the air: as discussed with equation (A-7), for plane waves the sound pressure of the difference-frequency wave is smaller than the starting pressure of the original wave(s) by a factor of the ratio of the difference and the original frequency. Conservatively taking a high infrasonic frequency of 20 Hz and a low ultrasonic one of 16 kHz, this ratio is 1/800: the infrasound pressure will be smaller by a factor of 800 or more than the ultrasound pressure emitted at the source, i.e., the level will be lower by 58 dB or more. With 1 m emitter size the plane-wave case is approximately fulfilled.

If one conservatively assumes an infrasound level required for vestibular effects of 140 dB (200 Pa rms pressure), then the ultrasound level at the source should be about 200 dB (200 kPa = twice atmospheric pressure, already in the strong-shock realm, a factor of 100 or 40 dB above the strongest ultrasound sources available). Such pressure would correspond to an intensity of 100 MW/m^2, which – integrated over the transmitter area of 0.79 m^2 – would mean a total acoustic power of 79 MW. For infrasound effects this would probably have to be maintained over a few seconds. Such a power level seems extremely difficult to achieve, even if direct conversion from 16,000 gasoline-air explosions per second in front of a reflector were used. Reducing the power by a smaller emitter size would not help, because then the beam width would begin to grow at a shorter distance, reducing the intensity and thus the non-linear-conversion efficiency. Quantitative analysis of this hypothetical fast sequence of strong shocks would need a separate study. In reality, an intensity on the order of 1 MW/m^2 at the source may be possible eventually (180 dB, bordering on weak shock where equation (A-7) holds, see the section on potential weapon sources), this would – due to the frequency ratio – be converted to a maximum level of 120 dB, which is harmless in the infrasound region.

Thus, it seems highly improbable that non-linear difference-frequency production in the air from ultrasound to infrasound can achieve levels at

which marked effects on the ear or the vestibular organ occur.

Second, conversion can take place by non-linear processes in the ear. Absent publications on difference-frequency infrasound production from high-level ultrasound in the ear, I do a simple estimate using plausible or conservative assumptions. The first is that as the sound frequency increases from the one of highest sensitivity, about 2 kHz for humans, towards the high hearing limit, the eardrum motion and consequent transfer to the inner ear decreases, mainly because of the inertia of the masses involved. For the cat, a decrease by a factor of 20 between 1 and 10 kHz has been observed;[134] conservatively, I take this value for 16 kHz and higher. Second, I use a conservatively simplified non-linear relationship between static pressure and the angle of the umbo (the eardrum centre where the malleus is connected). Again assuming vestibular effects from infrasound of 140 dB level, one arrives at a required ultrasound level of 180 dB (19 kPa) or more.

This is about a factor of 10 or 20 dB above the capabilities of the strongest periodic ultrasound sources available. Let us nevertheless assume that such levels could be produced. With standard assumptions, a 16-kHz wave starting with such level will become shocked already at 1.4 cm, after which strong absorption would start until the third, amplitude-invariant stage starts in 39 m with a level of 60 dB. Thus, the required level would be limited to the immediate vicinity of the hypothetical source. Here, however, direct damage to the ear by overload beyond the pain threshold is probable, and would represent the more drastic effect, together with heating even on bare skin (see the subsection on ultrasound).

Taking into account the conservative assumptions made, it seems therefore that neither of the non-linear mechanisms producing the difference (or modulation) frequency, in the air or in the ear, can generate anything close to inner-ear infrasound levels at which vestibular effects, or aural pain, would occur, except in the immediate vicinity of the source.

Producing an audible sound by non-linear processes in the air or in the ear where two inaudible (ultrasound) beams from separate sources intersect ("deference tone," see table 1) seems possible, on the other hand, since levels of a few tens of dB are sufficient for hearing.

Diffractionless Acoustic "Bullets"

For U.S. as well as Russian acoustic-weapon development, journalistic articles have reported non-diffracting acoustic "bullets," with, however, somewhat contradicting properties – in some reports they work at high, in others at low frequencies. For the U.S., antennas of 1-2 m size have been mentioned; in Russia, the bullets were said to be basketball-sized, with frequency of 10 Hz, and to be

selectable from non-lethal to lethal over hundreds of meters (see table 1).

It is not clear what might be behind these allegations. As shown in appendix 1, diffraction does occur with all three acoustic wave types – linear, weak – and strong-shock waves. Especially with low frequencies, diffraction provides for omnidirectional propagation, as demonstrated above. The "10 Hz" statement seems to imply a wavelength of 34 m, which does of course not fit at all to a "basketball-size" wave packet. But also with higher frequencies and even in case of shock, diffraction provides for eventual beam spreading, so that essentially constant-size propagation of a strong disturbance over "hundreds of meters" seems impossible with acoustic waves from sources of the order of 1 m. This holds at least as long as the signals produced at the different parts of the source are essentially similar and periodic.

There is a principal possibility of emitting different pulsed waveforms which vary in a controlled manner across the source area in such a way that their superposition produces a pulse which remains localized in a narrow beam for a substantially larger distance than with uniform excitation from the same source area. The beam width can be smaller than the source from the beginning, down to the order of a wavelength. However, if the source has finite size, as of course required for a real device, a far field with $1/r$ decrease of amplitude will occur eventually. Such waves have been called "diffraction-free" beams, acoustic (or electromagnetic) "missiles" or "bullets," acoustic (or electromagnetic) "directed-energy pulse trains." The conditions for this effect are: transient source signals of definite (space-variant) wave shape and wide bandwidth (i.e., substantial high-frequency content), and linear propagation. With respect to acoustics, first ultrasound experiments over tens of centimeters in water have demonstrated at least some increase of the on-axis intensity over the one from uniform continuous-wave excitation of the source array.[135] However, different from electromagnetics, in acoustics there are two counteracting effects. The first one is linear absorption which increases with the square of the frequency and thus successively reduces the high frequencies as the pulse propagates. Second, for strong sound non-linear propagation leads to shock formation which occurs the earlier, the higher the amplitude and the frequency. As mentioned in appendix 1, in the shock front unusual dissipative losses occur, leading to $1/r$ decrease for a beam of constant width. Unless a detailed theoretical study or experiments prove otherwise, a skeptical attitude seems advisable towards propagation of acoustic high-power pulses essentially without beam widening over distances much larger than possible with diffraction of uniform signals. It may turn out that, even though small-signal "pencil beams" prove feasible, at higher amplitude non-linear absorption destroys the effect.

Alternatively, one might think of a soliton, i.e., a one-pulse wave propagating in a non-linear medium in such a way that its amplitude and shape do not change. This requires that the higher speed of higher excitation caused by the non-linearity (see appendix 1) is counteracted by either dispersion or dissipation, and essentially one-dimensional propagation in a channel or tube, or as a plane wave of (essentially) infinite size.[136] In free air, however, dispersion at the frequencies of interest is negligible and dissipation is too low, as the process of shock formation demonstrates. Even in a soliton-carrying medium, in three dimensions the beam expands at distances large versus the source size, resulting in reduced amplitude.[137]

There is a further possibility, namely a vortex ring which – because of its rotational character – is not described by the normal wave equations. A vortex ring – the smoke ring is an example – is usually produced by ejecting a pulse of fluid through an orifice. At its margin, rotation is produced, and surrounding fluid is entrained, after which the rotating ring – by viscous interaction with the surrounding medium – moves as a stable entity through the latter. The fluid in the torus stays the same, thus a vortex ring can transport something, as demonstrated with the smoke particles in a smoke ring. During vortex-ring travel, viscous drag entrains more external fluid and produces a wake, thus the ring loses impulse, becoming larger and slower. It has to be noted that diffraction does not apply here, and that the size increase with distance is relatively slow. Finally, the ring breaks up into general turbulence.[138] Assessing the production, propagation, and effects of vortex rings could not be done here for time and space reasons.[139] If the purpose of the ring were not to exert pressure, but only to transport some material (hot gas, irritants, or the like), the rotation speed would be less important - but in this case the qualification as "acoustic" weapon, already somewhat questionable for vortex rings proper, would no longer apply, of course. Vortex rings are another area where an in-depth study is required.[140]

It may also be that journalists or observers misunderstood something. E.g., a focused beam of invisible laser light may have produced a plasma in front of a target emitting a shock wave (see below) – the propagation to the focus would of course not count as "acoustic." A misunderstanding is also suggested by the discrepancy concerning low or high frequency or by equating "non-diffracting" with "non-penetrating" (see table 1).

Plasma Created in Front of Target, Impact as by Blunt Object

In the defence press, the small arms program liaison of the U.S. Joint Services Small Arms Program was quoted as saying that an acoustic "bullet" would incapacitate by creating a "plasma in front of the target, which creates an

impact wave that is just like a blunt object. ... It causes blunt object trauma, like being hit by a baseball. Traditional bullets cause ripping, tearing. This is something different because the plasma causes the impact."[141]

Plasma creation would require overpressures of many megapascals, as they occur in the immediate vicinity of an exploding charge (and where indeed due to the temperature of several 1000 K the air does not only emit visible light, but is partially ionized).[142]

Accepting the "blunt-object" notion, the size of the shock wave would be at least comparable to the human-body size. This would mean that ears and lungs would be affected as well, with damage thresholds far below 1 MPa. Thus, shock-induced plasma with overpressures far above that would be certainly fatal. A second problem concerns the possibility of creating such strong shocks. Whereas with focused shock waves (i.e., implosions) pressures of even gigapascals can be achieved in the extremely small focus in the centre of a spherical shock tube,[143] projection to a distance much larger than the source, while avoiding spherical expansion with $1/r^3$ shock pressure decrease, seems unachievable (see above).

Thus, the possibility of plasma creation at a sizeable distance can be discarded. One can speculate whether the journalists have wrongly attributed it to acoustic weapons, whereas it was in fact meant for the pulsed chemical laser that is described one page later in the same article, again creating "a hot, high pressure plasma in the air in front of a target surface, creating a blast wave that will result in variable, but controlled effects on material and personnel."[144] In that case, the task of focusing over considerable distance would be alleviated by the short wavelength (on the order of $\propto$m) of the laser light, and high momentary power would be easier to achieve by using short pulses.

A similar argument holds if one asks whether "blunt-object trauma" could be produced by shock waves proper at some distance. An initially bounded wave would soon become larger than the human body and would fast diffract around it, creating about the same overpressure everywhere and exerting mainly compressive forces, which can be tolerated by tissue except at air-filled cavities. Only the drag of the moving air behind the shock front would exert a net force. For a conventional explosion a shock overpressure of about 100 kPa would be required, as it occurs with 1 kg TNT spherically exploding at only about 3 m distance.[145] At such pressure an incidence of eardrum rupture above 50% is already expected which would of course be the more dramatic injury.

Thus, blunt-object trauma is only probable very close to the shock-wave source and/or where a shock-wave beam has dimensions smaller than the human body. Also here the same mix-up with the laser-generated plasma has

probably occurred, and it was in fact mentioned in the same context.

The case of a vortex ring – acting only on parts of the body – needs a separate analysis, see above.

Localized Earthquakes Produced by Infrasound

An overview on non-lethal weapons has stated that acoustic weapons could affect buildings not only by shattering windows, but even by "localized earthquakes" (without giving an explicit source).[146] One might define an earthquake by a soil motion sufficient to endanger buildings, which occurs at a soil speed markedly above 10 mm/s.[147] Taking this as a conservative limit and using a maximum acoustic-seismic transfer factor of 10^{-5} m/(Pas),[148] a low-frequency sound pressure of 1 kPa (level 154 dB) is required to achieve that soil speed. As demonstrated above, such levels are possible only in the immediate vicinity of a low-frequency source, but cannot be maintained over tens of meters. Thus, if vibration levels damaging buildings are to be produced at all, they will probably not be transferred by vibration of the earth around them, but rather produced by resonances of or within the buildings, most likely within certain large rooms, directly excited by low-frequency sound energy. This could indeed produce "earthquake-like effects" inside, from rattling of tableware to breakage of windows, cracks in plaster, and in extreme situations even to collapse of brittle walls, but this would need very good coupling from the source (see also the section on protection). A misunderstanding of the phrase "earthquake-like" may be the basis of the allegation.

In a similar way, the alleged "disintegration of concrete" by infrasound,[149] which sounds as if it would occur on simple impinging and as such is incredible due to the large impedance mismatch, is only conceivable if a suitable building resonance could be exploited with good coupling from the source.[150] The same would hold for embrittlement or fatigue of metals, delamination of composite materials etc.[151]

Allegations Regarding Effects on Persons

There are a few allegations concerning high-power sound effects on humans which make a strong impression when being read, but are difficult to confirm from the scientific literature. This concerns mainly vomiting and uncontrolled defecation.[152]

Whereas vertigo or nausea in the vicinity of strong sound sources has been reported in scientific articles - often characterized as slight or transitory - actual vomiting was not reported with high audio frequencies nor with ultra-

sound (here dizziness seems rather to have been caused by audio contributions).[153] In close vicinity to jet engines, in a systematic study unsteadiness and imbalance were observed, but nausea occurred only in some employees sometimes after an exposure, and there was no vomiting. These authors mentioned "American reports" where one source had stated that at 13 kHz and 1 W power irritability and headache would be followed by nausea and even vomiting; however, no source for this was given.[154] Given that in other experiments people were exposed to 9.2, 10, 12, 15, and 17 kHz at levels of 140 to 156 dB for 5 minutes without any mentioning of even nausea,[155] without more information this single allegation of vomiting does not seem to deserve much weight. As to intense low-frequency sound, in the most extreme experiments carried out, mild nausea and giddiness were reported at 50 to 100 Hz with about 150 dB - but again vomiting did not occur.[156] With animals tested at low frequencies with up to 172 dB, vomiting was not mentioned at all.[157]

Evidence for bowel spasms and uncontrolled defecation is even scarcer. Among all the literature surveyed for this article, the only hint found was one on "digestive troubles" observed during experiments with a strong 16-Hz siren. These were, however, not specified at all, and the explanation immediately following talked of objects vibrating in clothing pockets.[158] In the low-frequency exposures up to 150 dB no bowel spasms were observed.[159] The same holds for low-frequency animal experiments.[160] Here it is noteworthy that also in reviewing vibration experiments no mention was made of bowel spasms or uncontrolled defecation.[161]

A third effect for which there seems to be no reliable source concerns resonances at very low frequencies of, e.g., the heart that might lead to death, as has been alleged - without further reference - in an early book.[162] Reference to the extreme 150-dB exposures at 50-100 Hz shows that the subjects suffered from several kinds of problems in the chest, but the heart - monitored by EKG - was not mentioned as troublesome.[163] Similarly, there are no indications for the alleged low-frequency-produced internal hemorrhages.[164]

Thus, it seems that these alleged effects are more based on hearsay than on scientific evidence. It cannot be excluded that at higher sound levels in specific frequency ranges, vomiting, uncontrolled defecation, or heart problems will occur, but the evidence for them is scant at best, and achieving such sound levels at some distance is extremely difficult anyway.

NOTES AND REFERENCES

1. A more detailed version of this article with more references and full appendices appears simultaneously: J. Altmann, *Acoustic Weapons - A Prospective Assessment. Sources, Propagation, and Effects of Strong Sound* (Ithaca NY: Peace Studies Program, Cornell University 1999).

2. Most of the information on non-lethal weapons comes from journalistic articles in the defence or general press. The following overview articles and books discuss various problems of non-lethal weapons and provide many references: R. Span, J. Altmann, G. Hornig, T. Krallmann, M. Rosario Vega Laso, J. Wüster, "'Non-lethal' Weapons - Fantasy or Prospect of More Humane Use of Force?" (in German), Dossier Nr. 17, Wissenschaft und Frieden (June 1994); R. Kokoski, "Non-lethal weapons: a case study of new technology developments," in: *SIPRI Yearbook 1994: World Armaments and Disarmament* (Stockholm/Oxford: SIPRI/Oxford University Press, 1994): 367-386; S. Aftergood, "The Soft-Kill Fallacy," *Bulletin of the Atomic Scientists* (Sept./Oct. 1994): 40-45; A. Roland-Price, "Non-Lethal Weapons: A Synopsis," in: U.S. Congress, Office of Technology Assessment, "Improving the Prospects for Future International Peace Operations - Workshop Proceedings," OTA-BP-ISS-167 (Washington DC: U.S. Government Printing Office, Sept. 1995); J. Altmann, "'Non-Lethal' Weapons," in: J. Rotblat (ed.), *Security, Cooperation and Disarmament: The Unfinished Agenda for the 1990s* (Singapore etc.: World Scientific, 1998); M. Dando, *A New Form of Warfare - The Rise of Non-Lethal Weapons* (London/Washington: Brassey's, 1996); N. Lewer, S. Schofield, *Non-Lethal Weapons: A Fatal Attraction? Military Strategies and Technologies for 21st-Century Conflict* (London/New Jersey: Zed Books, 1997). There are not many systematic and comprehensive publications by proponents of non-lethal weapons. The following references give some examples of proponents' writing: "Nonlethality: A Global Strategy Whitepaper" (Washington DC: U.S. Global Strategy Council, 1992); J. B. Alexander, "Nonlethal Weapons and Limited Force Options," presented to Council of Foreign Relations, New York, 27 Oct. 1993; Milt Finger, "Technologies to Support Peacekeeping Operations," in: U.S. Congress, Office of Technology Assessment (ibid.); G. Yonas, "The Role of Technology in Peace Operations"; in: U.S. Congress, Office of Technology Assessment (ibid.); C. Morris, J. Morris, T. Baines, "Weapons of Mass Protection - Nonlethality, Information Warfare, and Airpower in the Age of Chaos," *Airpower Journal* 9, no. 1 (Spring 1995): 15-29; D. A. Morehouse, *Nonlethal Weapons - War Without Death* (Westport CT/London: Praeger, 1996). For a balanced view from inside the U.S. military, see: J. W. Cook III, D. P. Fiely, M. T. McGowan, "Nonlethal Weapons - Technologies, Legalities, and Potential Policies," *Airpower Journal* 9, Special Issue (1995): 77-91. NLW developments for law-enforcement purposes are presented in considerable detail e.g. in: J. Alexander, D. D. Spencer, S. Schmit, B. J. Steele (eds.), "Security Systems and Nonlethal Technologies for Law Enforcement," *Proc. SPIE* 2934 (1997). All kinds of activity are described in the contributions to the conference of the National Defense Industrial Association "Non-Lethal Defense III," Johns Hopkins University, 25 and 26 Febr. 1998, http://www.dtic.mil/ndia/NLD3/index.html.

3. Morehouse (note 2).

4. E.g.: A. W. Debban, "Disabling Systems: War-Fighting Option for the Future," *Airpower Journal* 7, no. 1 (Spring 1993): 44-50; Roland-Price (note 2).

5. It seems that other Western industrialized countries rather take a wait-and-see approach, mainly doing paper studies to keep up to date, see: Altmann 1996 (note 2); reports from Russia indicate that there is considerable interest in non-lethal weapons as well, examples include directed-energy weapons and an acoustic bullet, see: Kokoski

(note 2), 373; M. T., "Russians Continue Work on Sophisticated Acoustic Weaponry," *Defense Electronics* 26, no. 3 (March 1994): 12.

6. These considerations may have been among the motives in the recent rethinking by the U.S. of its position towards laser blinding weapons. In June 1995 the Department of Defense was on the verge of buying 50 LCMS laser blinding rifles and planned to acquire 2,500 more. But in September 1995 it changed its policy, and in December 1995 (after the wording had been changed to accommodate US and other interests) the U.S. signed the new Additional Protocol to the UN Convention on Prohibitions or Restrictions on the Use of Certain Conventional Weapons Which May Be Deemed to Be Excessively Injurious or to Have Indiscriminate Effects ("Certain Weapons Convention," "Inhumane Weapons Convention") of 1980. See: "Blinding Laser Weapons: The Need to Ban a Cruel and Inhumane Weapon," *Human Rights Watch Arms Project* 7, no. 1 (Sept. 1995); text of the Protocol in: "Trust and Verify," no. 62 (London: Verification Technology Information Centre, Nov./Dec. 1995).

7. The Biological Weapons Convention of 1972 bans any hostile use of biological agents, irrespective of whether the target is a living organism or equipment; Finger (note 2) is wrong in this respect. See: Altmann 1996 (note 2); Cook et al. (note 2). However, the Chemical Weapons Convention of 1992 only prohibits toxic chemicals which can cause death, temporary incapacitation or permanent harm to humans or animals.

8. The most prominent example is the case of laser blinding weapons, use of which fortunately has been banned in 1995, see note 6.

9. See also: B. Starr, "Non-lethal weapon puzzle for US Army," *International Defense Review* 4 (1993): 319-320.

10. Morehouse (note 2), p. 119.

11. Such assessment of new military technologies is one part of preventive arms limitations; for examples of other technologies see: J. Altmann, "Verifying Limits on Research and Development - Case Studies: Beam Weapons, Electromagnetic Guns," in: J. Altmann, T. Stock, J.-P. Stroot (eds.), *Verification After the Cold War - Broadening the Process* (Amsterdam: VU Press, 1994).

12. Additional sources not included in the table: B. Starr, "U.S. tries to make war less lethal," *Jane's Defence Weekly* (31 Oct. 1992): 10; A. and H. Toffler, "War and Anti-War. Survival at the Dawn of the 21st Century" (Boston etc.: Little, Brown and Co. 1993) (here: ch. 15, "War without Bloodshed?") (quoted after the German translation: "Überleben im 21. Jahrhundert" (Stuttgart: DVA 1994)); Debban (note 4). Alexander (note 2); J. Barry, T. Morganthau, "Soon, 'Phasers on Stun,'" *Newsweek* (7 Febr. 1994): 26-28; Kokoski (note 2); Aftergood (note 2), G. Frost, C. Shipbaugh, "GPS Targeting Methods for Non-Lethal Systems," Reprint RAND/RP-262 (1996) (reprinted from IEEE Plans 94); Cook et al. (note 2); Morehouse (note 2), p. 20, 119 f.; Dando (note 2), p. 11 ff; SARA report of 10 Febr. 1995 (revised 13 Febr. 1996) and other references as reported by: W. Arkin, "Acoustic Anti-personnel Weapons: An Inhumane Future?," *Medicine, Conflict and Survival* 14, no. 4 (1997): 314-326.

13. M. Lumsden, *Anti-personnel Weapons* (Stockholm/London: SIPRI/Taylor&Francis 1978): 203-205.

14. "Army tests new riot weapon," *New Scientist* (20 September 1973): 684; C. Ackroyd, K. Margolis, J. Rosenhead, T. Shallice, *The Technology of Political Control* (2nd ed.) (London: Pluto, 1980): 224-225. See also: R. Rodwell, "'Squawk box' technology," *New Scientist* (20 September 1973): 667.

15. "Non-lethality ..." (note 2).

16. V. Kiernan, "War over weapons that can't kill," *New Scientist* (11. Dec. 1993): 14-16.

17. Lewer/Schofield (note 2), 8 ff.

18. P. R. Evancoe, "Non-Lethal Technologies Enhance Warrior's Punch," *National Defense* (Dec. 1993): 26-29.

19. M. Tapscott, K. Atwal, "New Weapons That Win Without Killing On DOD's Horizon," *Defense Electronics* (Febr. 1993): 41-46.

20. Starr (note 9).

21. "Army Prepares for Non-Lethal Combat," *Aviation Week & Space Technology* (24 May 1993): 62.

22. M. T. (note 5).

23. N. Broner, "The Effects of Low Frequency Noise on People - A Review," *Journal of Sound and Vibration* 58, no. 4 (1993): 483-500; O. Backteman, J. Köhler, L. Sjöberg, "Infrasound - Tutorial and Review: Part 4," *Journal of Low Frequency Noise and Vibration* 3, no. 2 (1984): 96-113. Broner cites: J. F. J. Johnston, *Infrasound - a Short Survey* (Royal Military College of Science, England, 1971). Backteman et al. have copied the respective paragraph from Broner virtually identically, leaving out two sentences and two references, without giving the source.

24. R. Applegate, *Riot Control - Material and Techniques* (Harrisburg PA: Stackpole, 1969): 273.

25. Applegate (note 24), 271-273. In 1973 the British government bought 13 such systems for the use in Northern Ireland, but they seem to not have been used there. See: Ackroyd et al. (note 14), 223-224.

26. Johnston (note 23), quoted in Broner (note 23). For the use of white noise on prisoners see also: Lumsden (note 13) and references given there.

27. "Army tests ..." (note 14); Ackroyd et al. (note 14), 224-225. See also: Rodwell (note 14).

28. In a subsequent press conference, the British Army instead presented the 350-W amplifier/speaker system (see note 24) of which 13 copies had been bought, but "forgot" to invite the *New Scientist* reporter who had written the "squawk box" article, see: R. Rodwell, "How dangerous is the Army's squawk box?," *New Scientist* (27 September 1973): 730.

29. Ackroyd et al. (note 14), 224-225.

30. M. Bryan, W. Tempest, "Does infrasound make drivers drunk?," *New Scientist* (16 March 1972): 584-586; R. Brown, "What levels of infrasound are safe?," *New Scientist* (8 Nov. 1973): 414-415; H. E. von Gierke, D. E. Parker, "Infrasound," ch. 14 in: W. D. Keidel, W. D. Neff (eds.), "Auditory System - Clinical and Special Topics," *Handbook of Sensory Physiology,* vol. V/3 (Berlin etc.: Springer, 1976): section VII.

31. Starr (note 9).

32. Tapscott/Atwal (note 19). See also: http://www.pica.army.mil/pica/products/tbiwc.html.

33. Starr (note 9). See also: http://www.sara.com/documents/future.htm. Similar infor-

mation is provided by Tapscott/Atwal (note 19); they state that Los Alamos National Laboratory (LANL) is involved in acoustic beams, too, whereas Starr mentions LANL only for optical munitions and high-power microwave projectiles. A LANL brochure on non-lethal weapons contains the latter two, but not acoustic weapons: "Special Technologies for National Security" (Los Alamos NM: Los Alamos National Laboratory, April 1993).

34. M. T. (note 5).

35. SARA Report, 10 February 1995 (revised 13 February 1996) and other references as reported by Arkin (note 12).

36. With infrasound, no pain or nausea was observed even up to 172 dB, see section 2.2 below. With audible sound, there was no physical trauma and damage to tissues up to above 150 dB, see 2.3.

37. Tens of meters are more realistic, see appendix 2.

38. Note that the infrasound research seems to have been refocused recently, see: J. Hecht, "Not a sound idea," *New Scientist*, 20 March 1999, 17.

39. E.g., vertigo, nausea, and vomiting are ascribed to infrasound at 130 dB (correct: none to 172 dB, see section 2.2.3.2 below), and a blast wave would lead to eardrum rupture at 130 dB (correct: above 185 dB, see 2.5): Kap. 3.8, see "Konzeptbeschreibungen akustischer Wirkmittel" in J. Müller et al., *Nichtletale Waffen, Abschlußbericht*, Band II, Dasa-VA-0040-95=OTN-035020, Daimler-Benz Aerospace, 30. 4. 1995, 307-333.

40. A. Dähn, "Angriff auf das Trommelfell"; *Berliner Zeitung*, 24 March 1999; K.-D. Thiel, "Non-Lethal Weapons Activities at ICT," in *Non-Lethal Defense III* (note 2), file ict.pdf.

41. Lumsden (note 13); L. Liszka, "Sonic Beam Devices - Principles" in *Expert Meeting on Certain Weapon Systems and on Implementation Mechanisms in International Law*, Geneva, 30 May - 1 June 1994, Report (Geneva: International Committee of the Red Cross, July 1994), 89-91.

42. Arkin (note 12).

43. My subject is only sound in air. Potential underwater applications, e.g., against divers or animals, need a separate study.

44. For transient pressure variations the level is often defined using the maximum pressure occurring, not the rms value.

45. For a discussion of blast weapons, see Lumsden (note 13) chap. 6.

46. SARA (note 12).

47. For space reasons, in the section on effects several details and references have been left out. For the complete information see Altmann (note 1).

48. F. G. Hirsch, "Effects of Overpressure on the Ear - A Review," *Annals of the New York Academy of Sciences* 152(Art. 1) (1968): 147-162; W. D. Keidel, W. D. Neff (eds.), "Auditory System - Anatomy, Physiology (Ear)," in *Handbook of Sensory Physiology*, vol. V/1 (Berlin etc.: Springer, 1974); Karl D. Kryter, *The Effects of Noise on Man* (New York etc.: Academic 1970; second edition 1985), ch. 1; v. Gierke/Parker (note 30); W. Melnick, "Hearing Loss from Noise Exposure," in C. M. Harris (ed.), *Handbook of Acoustical Measurements and Noise Control* (New York etc.: McGraw-Hill, 1991) ch. 18; W. D. Ward, "Noise-Induced Hearing Damage," in M. M. Paparella et al. (eds.), *Oto-*

laryngology vol. II (3rd edition Philadelphia etc.: Saunders 1991) ch. 45; B. Berglund, P. Hassmén, "Sources and effects of low-frequency noise," *Journal of the Acoustical Society of America* 99(5) (May 1996): 2985-3002.

49. H.-G. Boenninghaus mit T. Lenarz, Hals-Nasen-Ohrenheilkunde für Studierende der Medizin, 10. Aufl., Berlin etc.: Springer, 1996.

50. Note that PTS can accumulate over a long time even if recovery from TTS occurs daily.

51. Note that sometimes also long-term injury comes under this heading, and damage from short exposure is called acute acoustic trauma.

52. Loudness is measured by comparing subjective perception of tones at other frequencies with the one at 1 kHz. At 1 kHz, loudness levels in phone are defined to be equal to the respective sound pressure levels in decibels.

53. N. S. Yeowart, M. J. Evans, "Thresholds of audibility for very low-frequency pure tones," *Journal of the Acoustical Society of America* 55, no. 4 (April 1974): 814-818; A. M. Small, Jr., R. S. Gales, "Hearing Characteristics," in Harris (note 48), chap. 17. H. Møller, J. Andresen, "Loudness of Pure Tones at Low and Infrasonic Frequencies," *Journal of Low Frequency Noise and Vibration* 3, no. 2 (1984): 78-87; Berglund/Hassmén (note 48); Melnick (note 48); H. E. von Gierke, C. W. Nixon, "Effects of Intense Infrasound on Man," in W. Tempest (ed.), *Infrasound and Low Frequency Vibration* (London etc.: Academic, 1976), ch. 6, 134; v. Gierke/Parker (note 30), 604.

54. E.g. see the sensational article "The Low-Pitched Killer - Can sounds of silence be driving us silly" (*Melbourne Sunday Press*, 7 Sept. 1975), reproduced in Broner (note 23); see also note 30. Within science, it is interesting what Lumsden writes about a meeting of the British Association on the Advancement of Science where the "Director of the [British] Noise Abatement Society reported that at a research centre at Marseille, France, an infrasound generator had been built which generated waves at 7 Hz. He said that when the machine was tested, people in range were sick for hours. The machine could cause dizziness, nervous fatigue and 'seasickness' and even death up to 8 km away (*Associated Press*, Leicester, England, 9 September 1972)." Lumsden (note 13), 204. This obviously refers to Gavreau's work done at Marseille, see V. Gavreau, R. Condat, H. Saul, "Infra-Sons: Générateurs, Détecteurs, Propriétés physiques, Effets biologiques," *Acustica* 17, no. 1 (1966): 1-10; V. Gavreau, "Infrasound," *Science Journal* 4, no. 1 (Jan. 1968): 33-37. Note that today scientists at the same institute have some doubts about the conclusions drawn by Gavreau on the effects of infrasounds, because his experiments and observations have not been replicated and confirmed under accurate experimental conditions. G. Canevet, Laboratoire de Mécanique et d'Acoustique CNRS, Marseille, personal communication.

55. Thus, in the determination of the capabilities of hearing much care is needed to keep nonlinearities in sound production very low lest the externally generated harmonics at higher and better audible frequencies lead to erroneously high values.

56. With dogs and cats, less pathological damage was observed. On the other hand, thirty seconds of exposure to 172 dB infrasound did not even produce reddening in a human eardrum.

57. There is one documented case where at 6.5 kHz, a small rupture and blood in the external ear canal was observed with one experimenter after 5 minutes exposition to about 158 dB (1.6 kPa): H. Davis, H. O. Parrack, D. H. Eldredge, "Hazards of Intense Sound and Ultrasound," *Annals of Otology, Rhinology, Laryngology* 58 (1949): 732-738.

58. C. Mohr, J. N. Cole, E. Guild, H. E. von Gierke, "Effects of Low Frequency and Infrasonic Noise on Man," *Aerospace Medicine* 36, no. 9 (1965): 817-824. Concerning the stronger effects at low audio frequencies reported by Mohr et al., note that there are doubts at the same laboratory today whether these were due to oil droplets in the compressor air and not to the sound. The experiments are to be repeated in 1999. R. McKinley, Aural Displays and Bioacoustics Branch, Air Force Research Laboratory, Wright-Patterson Air Force Base, OH, U.S., personal communication.

59. Humans can stand quite high accelerations. In experiments with frequencies between 1 and 25 Hz, the subjective tolerance was reached at a few times the normal gravity acceleration ($g=9.8\ m/s^2$); subjects suffered, inter alia, from dyspnoea, chest and periumbilical pain, and sometimes gastrointestinal bleeding. However, no lasting effects were observed.

60. If the sound pressure would affect only a part of the body surface, sideward movement and shear waves in the tissue would result with much greater energy deposition.

61. Note that for near-daily exposition of humans over 10 years to short tones, much lower damage-limiting levels of 130 to 115 dB were estimated. For the maximum instantaneous sound pressure occurring in an isolated event during a working day, 200 Pa (140 dB) has been given.

62. See note 57.

63. The authors described a "most unpleasant and disturbing sensation of general instability and weakness"; nausea, true dizziness, visual disturbances, or nystagmus were not observed. Ear protection stopped the effect. See E. D. D. Dickson, D. L. Chadwick, "Observations on Disturbances of Equilibrium and Other Symptoms Induced by Jet Engine Noise," *Journal of Laryngology and Otology* 65 (1951): 154-165. This seems to be the only article which reasonably reliably and completely describes the symptoms and circumstances of equilibrium disturbances close to jet engines. Later studies of ground or flight-deck personnel do not mention equilibrium problems, even though personnel was exposed to levels up to above 140 dB, often without ear protection. Dickson/Chadwick of 1951 was cited to the 80s.

64. Among the about 1800+450 articles produced by a Medline search for (injury or impairment) and (sound or noise or ultrasound), or (acoustic trauma), respectively, from 1966 to 1998, I have only found four (potentially) describing injury due to tonal or broad- or narrow-band noise of level about or above 140 dB. On the other hand, there are many articles about damage due to impulse noise of levels of 150 dB and more, see section 2.5 in Altmann (note 1).

65. Rats and mice were killed by overheating within minutes at audio and ultrasound frequencies.

66. Pulses of fast rise time and duration above 3 ms, produced at repetition rates of 6-30/min to no more than 100 at one exposure, would not cause excessive hearing loss in 75% of the exposed people.

67. Knocking a person down, which occurs with nuclear blasts of 0.5 to 1 s duration at 7-10 kPa overpressure (171-174 dB), see G. F. Kinney, K. J. Graham, *Explosive Shocks in Air* (New York etc.: Springer, 1985), table XV, is not relevant with shock waves from conventional explosions. Durations of conventional-explosion shock waves are only a few ms and thus the impulse transferred, i.e., the time integral over the drag force, is correspondingly smaller for equal peak overpressure. Only at very close distance (below a few meters) would the impulse suffice, but here other damage (to the ear-

drum, the lungs) would be more relevant, see appendix 1.

68. For this and the following examples see also: D. L. Johnson, "The Effects of High Level Infrasound," in: H. Møller, P. Rubak (eds.), *Conference on Low Frequency Noise and Hearing*, 7-9 May 1980, Aalborg, Denmark.

69. See Altmann (note 1), appendix A.4.

70. N. S. Yeowart, M. E. Bryan, W. Tempest, "The Monaural M.A.P. Threshold of Hearing at Frequencies from 1.5 to 100 c/s," *Journal of Sound and Vibration* 6 (1967): 335-342; see also: M. J. Evans, "Physiological and Psychological Effects of Infrasound at Moderate Intensities," in *Tempest* (note 53) chap. 5.

71. N. S. Yeowart, M. E. Bryan, W. Tempest, "Low-frequency Noise Thresholds," *Journal of Sound and Vibration* 9 (1969): 447-453; see also: v. Gierke/Nixon (note 53).

72. D. L. Johnson, "Various Aspects of Infrasound," in L. Pimonow (ed.), *Colloque international sur les infra-sons* (Paris: Centre National de Recherche Scientifique, 1974): 129-153, cited after: v. Gierke/Parker (note 30). Fig. 2 in v. Gierke/Nixon (note 53) shows "piston stroke 12 cm d.a."

73. Assuming a large baffle, from equation (A-10) in: Altmann (note 1).

74. For an overview over natural sources, see T. B. Gabrielson, "Infrasound" in M. J. Crocker (ed.), *Encyclopedia of Acoustics* (New York etc.: Wiley, 1997) ch. 33, and literature cited there. Note that for very slow pressure variations the Eustachian tube provides equalization of the middle-ear pressure.

75. R. D. Hill, "Thunder" in R. H. Golde (ed.), *Lightning*, vol. 1 (London etc.: Academic, 1977) chap. 11.

76. Johnson (note 68); own calculations.

77. Backteman et al. (note 23); Berglund/Hassmén (note 48).

78. Backteman et al. (note 23).

79. Johnson (note 68); v. Gierke/Nixon (note 53).

80. From own measurements of MiG-21 and Tornado fighter-bombers, see J. Altmann, R. Blumrich, "Acoustic and Seismic Signals during Aircraft Take-offs and Landings" (in German) in *Fortschritte der Akustik - DAGA 94* (Bad Honnef: DPG-GmbH. 1994): 417-420; R. Blumrich, *Sound Propagation and Seismic Signals of Aircraft used for Airport Monitoring - Investigations for Peace-keeping and Verification* (Hagen: ISL, 1998).

81. Mohr et al. (note 58); v. Gierke/Parker (note 30).

82. v. Gierke/Nixon (note 53).

83. v. Gierke/Nixon (note 53); v. Gierke/Parker (note 30).

84. H. C. Sommer, C. W. Nixon, "Primary components of simulated air bag noise and their relative effects on human hearing," Report, AMRL-TR-73-52 (Wright-Patterson Air Force Base OH: Aerospace Medical Research Laboratory 1973), cited after: v. Gierke/Parker (note 30), section V; Johnson (note 68).

85. H. G. Leventhall, "Man-made infrasound - its occurrence and some subjective effects" in Pimonow (note 72), quoted after v. Gierke/Nixon (note 53).

86. For general articles on loudspeaker arrays, see the special issue of *Journal of the Audio Engineering Society Audio/Acoustics/Applications* 38, no. 4 (April 1990).

87. With layers of extremely porous, but stiff aerogels on the membrane, impedances could match and coupling could be much improved. This possibility is also mentioned by Finger (note 2).

88. For the efficiency figures see: B. M. Starobin, "Loudspeaker Design" in Crocker (note 74) chap. 160; see also V. Salmon, "Horns," in Crocker (note 74) ch. 61, and literature cited there.

89. The 40° held for the 68 cm long exponential horns with combined diameter 71 cm; there was also a 2.1 m long extension. R. C. Jones, "A Fifty Horsepower Siren," *Journal of the Acoustical Society of America* 18, no. 2 (Oct. 1946): 371-387.

90. C. H. Allen, I. Rudnick, "A Powerful High Frequency Siren," *Journal of the Acoustical Society of America* 19, no. 5 (Sept. 1947): 857-865; C. H. Allen, H. Frings, I. Rudnick, "Some Biological Effects of Intense High Frequency Airborne Sound," *Journal of the Acoustical Society of America* 20, no. 1 (Jan. 1948): 62-65.

91. H. O. Parrack, "Ultrasound and Industrial Medicine," *Industrial Medicine and Surgery* 21, no. 4 (April 1952): 156-164.

92. J. Sabatier, "Acoustical Characterization of the Mother of All Speakers" (master's thesis, National Center for Physical Acoustics,1993); <http://w3.arl.mil/tto/ARLDTT/FoxProdata/fac50.html>.

93. Assuming that the sound pressure is approximately equal across the 2.3 m wide mouth, the area ratio to the equivalent 1-m-radius sphere emitting 20 kW results in about 4.8 kW/m^2 (157 dB). Spherical spreading with 1/r^2 decrease of intensity can be assumed already close to the mouth. Note also that there is frequency-dependent directivity: the sound pressure decreases off the horn axis the faster, the higher the frequency (but above the frequency where the first null of (A-4) occurs the decrease is not monotonical because of sidelobes). With a slightly smaller horn of 2.1 m diameter, at 40 Hz (ka=0.8) the intensity was still essentially the same in all directions.

94. E.g., with meter-size enlarged models of police whistles or Levavasseur whistles 196 and 37 Hz have been produced at up to about 2 kW power, more would have been possible with higher air flow and larger whistles. See: Gavreau et al. 1966 (note 54); see also: Gavreau 1968 (note 54).

95. Yu. Ya. Borisov, "Acoustic Gas-Jet Generators of the Hartmann Type," in L. D. Rozenberg (ed.), *Sources of High-Intensity Ultrasound* (New York: Plenum 1969) part I; see also Parrack 1952 (note 91); H. Kuttruff, "Physik und Technik des Ultraschalls" (Stuttgart: Hirzel, 1988): 140 f.

96. J. A. Gallego-Juarez, G. Rodriguez-Corral, L. Gaete-Garreton, "An ultrasonic transducer for high power applications in gases," *Ultrasonics* 16 (November 1978): 267-271.

97. According to equation (A-14) to (A-24) in Altmann (note 1).

98. J. A. Gallego-Juarez, L. Gaete-Garreton, "Experimental Study of Nonlinearity in Free Progressive Acoustic Waves in Air at 20 kHz," 8e Symposium International sur l'acoustique non linéaire, *Journal de Physique* 41, Colloque C-8, suppl. au no. 11 (Nov. 1979): C8-336 - C8-340; the total level was estimated from the levels of the individual harmonics.

99. Altmann (note 1), appendix A.4 and fig. A.2.

100. Altmann (note 1), appendix A.4.

101. Megawatt power was mentioned by SARA (note 12).

102. Altmann (note 1), section 3.2.

103. For treatments of slightly related problems see: Y. Inoue, T. Yano, "Propagation of strongly nonlinear plane waves," *Journal of the Acoustical Society of America* 94, no. 3 pt. 1 (Sept. 1993): 1632-1642; Y. Inoue, T. Yano, "Strongly nonlinear waves and streaming in the near field of a circular piston," *Journal of the Acoustical Society of America* 99, no. 6 (June 1996): 3353-3372.

104. The DASA report discusses concepts of a 0.5 kg whistling system for hand throwing to 10-50 m (working about 30 seconds), and a 5 kg system for air-gun delivery to 300 m from a small truck (duration about 5 minutes), both producing 120 dB in 1 m at 1-10 kHz, see: Müller (note 39).

105. C. W. Nixon, E. H. Berger, "Hearing Protection Devices" ch. 21 in Harris (note 48). For individual attenuation values, including the helmet, see J. C. Webster, P. O. Thompson, H. R. Beitscher, *Journal of the Acoustical Society of America* 28, no. 4 (July 1956): 631-638.

106. G. Jansen, "Influence of High Noise Intensities on the Human Organism" (in German), Wehrmedizinische Monatsschrift no. 10 (1981): 371-379.

107. R. Moulder, "Sound-Absorptive Materials," in Harris (note 48) chap. 30

108. For a rectangular room, half of the longest resonance wavelength equals the longest dimension. Thus, e.g., for 5 m length 34 Hz is the lowest resonance frequency.

109. There is of course a considerable body of medical literature on aural injuries and their treatment, see e.g.: Paparella et al. (note 48). Therapy for sub-lethal blast damage to other organs than the ear will not be discussed here, because the ear damage will be prominent, and because the former does not come under the "acoustic" rubric.

110. Ward 1991 (note 48). See also R. Probst et al., "A Randomized, Double-blind, Placebo-controlled Study of Dextran/Pentoxifylline Medication in Acute Acoustic Trauma and Sudden Hearing Loss," Acta Otolaryngologica (Stockholm) 112, no. 3 (1992): 435-443.

111. Ward 1991 (note 48).

112. R. H. Chait, J. Casler, J. T. Zajtchuk, "Blast Injury of the Ear: Historical Perspective," *Annals of Otology, Rhinology & Laryngology* 98, no. 5 pt. 2, Suppl. 140 (May 1989): 9-12; J. D. Casler, R. H. Chait, J. T. Zajtchuk, "Treatment of Blast Injury to the Ear," *Annals of Otology, Rhinology & Laryngology* 98, no. 5 pt. 2, Suppl. 140 (May 1989): 13-16; and respective references.

113. See e.g.: A. G. Kerr, J. E. T. Byrne, "Concussive effects of bomb blasts on the ear," *Journal of Laryngology and Otology* 89, no. 2 (Febr. 1975): 131-143.

114. Papers of International Cochlear Implant, Speech and Hearing Symposium, *Annals of Otology, Rhinology & Laryngology* 104, no. 9 pt. 2, Suppl. 166/ (Sept. 1995): 1-468; for acquired deafness with potential induction by noise see J. S. Thomas, "Cochlear Implantation in the Elderly," ibid., pp. 91-93; R. K. Shepherd et al., "The Central Auditory System and Auditory Deprivation: Experience with Cochlear Implants in the Congenitally Deaf," Acta Otolaryngologica (Stockholm) Supplement 532 (1997): 28-33; M. J. A. Makhdoum, A. F. M. Snik, P. van den Broek, "Cochlear implantation: a review of the literature and the Nijmegen results," *Journal of Laryngology and Otology* 111 (Nov. 1997): 1008-1017; papers of third European Symposium

on Pediatric Cochlear Implantation, *American Journal of Otology* 18, no. 6 Suppl. (Nov. 1997): S1-S172.

115. Ward 1991 (note 48).

116.L. Doswald-Beck (ed.), "Blinding Weapons: Reports of the Meetings of Experts Convened by the International Committee of the Red Cross on Battlefield Laser Weapons, 1989-1991" (Geneva: International Committee of the Red Cross 1993): 336; "Blinding laser weapons ..." (note 6): 28 ff.

117. R. M. Coupland (ed.), "The SIrUS Project - Towards a determination of which weapons cause 'superfluous injury or unnecessary suffering'" (Geneva: International Committee of the Red Cross, 1997).

118. For details, see appendices A.1-A.4 of Altmann (note 1).

119. E.g.: E. Skudrzyk, *The Foundations of Acoustics - Basic Mathematics and Basic Acoustics* (New York/Wien: Springer, 1971); P. M. Morse, K. U. Ingard, *Theoretical Acoustics* (New York etc.: McGraw-Hill, 1968); A. D. Pierce, *Acoustics - An Introduction to Its Physical Principles and Applications* (Woodbury NY: Acoustical Society of America, 1991).

120. Without the pipe, acoustic short-circuit between the front and back of the piston would occur at low frequencies - this is the reason why loudspeakers are usually mounted in closed boxes.

121. See also: H. Levine, J. Schwinger, "On the Radiation of Sound from an Unflanged Circular Pipe," *Physical Review* 73 (1948): 383-406.

122. See e.g.: Salmon (note 88) and literature cited there.

123. Starobin (note 88).

124. See e.g.: O. V. Rudenko, S. I. Soluyan, *Theoretical Foundations of Nonlinear Acoustics* (New York/London: Consultants Bureau, 1977); G. B. Whitham, *Linear and Nonlinear Waves* (New York etc.: Wiley, 1974); M. F. Hamilton, D. T. Blackstock (eds.), *Nonlinear Acoustics* (San Diego etc.: Academic, 1998).

125. Non-linear sound propagation and the interaction with diffraction and absorption are fields of active research. Especially for pulsed sources, there is a need for more work, see the concluding remarks of: J. N. Tjøtta, S. Tjøtta, "Nonlinear Equations of Acoustics" in M. F. Hamilton, D. T. Blackstock (eds.), *Frontiers of Nonlinear Acoustics: Proceedings of 12th ISNA* (London: Elsevier, 1990): 80-97. For on-going research, see the series of International Symposia on Non-linear Acoustics.

126. See e.g.: Rudenko/Soluyan (note 124).

127. Ya. B. Zel'dovich, Yu. P. Raizer, *Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena*, vol. I (New York/London: Academic Press, 1966); Whitham (note 124); S. Glasstone, P. J. Dolan, "The Effects of Nuclear Weapons" (Washington DC: Government Printing Office, 1977) (ch. III); Kinney/Graham (note 67).

128. W. D. Ward, W. Selters, A. Glorig, "Exploratory Studies on Temporal Threshold Shift from Impulses," *Journal of the Acoustical Society of America* 33, no. 6 (June 1961): 781-793.

129. For details, see: Altmann (note 1), section 5. and appendices A.5-A.7.

130. The detailed analysis, including estimates from 500 Hz to 10 kHz, is given in: Altmann (note 1), appendix A.5.

131. "Army tests ..." (note 14).

132. Liszka (note 41).

133. Both cases are treated in: Altmann (note 1), appendix A.6.

134. J. J. Guinan, Jr., W. T. Peake, "Middle-Ear Characteristics of Anesthetized Cats," *Journal of the Acoustical Society of America* 41, no. 5 (1967): 1237-1261. Note that in their anesthetized animals the middle-ear muscles were relaxed so that the aural reflex reducing transmission was not working. Thus the estimate made here is even more conservative.

135. There is much more literature on electromagnetic and optical than on acoustic narrow pulsed beams, and much more theoretical work than experimental. See e.g.: R. W. Ziolkowski, "Localized transmission of electromagnetic energy," *Physical Review* A 39, no. 4 (Febr. 15, 1989): 2005-2033, and references cited therein; Gang Wang, Wen Bing Wang, "Beam characteristics of short-pulse radiation with electromagnetic missile effect," *Journal of Applied Physics* 83, no. 10 (15 May 1998): 5040-5044. Note that the "bullet" notion is even used for a pulse "shot" through a conically expanding "rifle": A. Stepanishen, "Acoustic bullets/transient Bessel beams: Near to far field transition via an impulse response approach," *Journal of the Acoustical Society of America* 103, no. 4 (April 1998): 1742-1751. For the ultrasound experiment see: R. W. Ziolkowski, D. K. Lewis, "Verification of the localized-wave transmission effect," *Journal of Applied Physics* 68, no. 12 (15 Dec. 1990): 6083-6086.

136. E.g.: E. Infeld, G. Rowlands, *Nonlinear waves, solitons and chaos* (Cambridge etc.: Cambridge University Press 1990); M. Remoissenet, "Waves Called Solitons - Concepts and Experiments," (Berlin etc.: Springer 1994).

137. For a discussion of non-amplitude-preserving collapsing or expanding "solitons" in two- or three-dimensional plasma and other media, see Infeld/Rowlands (note 136), chap. 9.

138. For vortex-ring dynamics, see: H. Lamb, *Hydrodynamics* (6th edition, Cambridge: Cambridge University Press 1932), chap. VII; P. G. Saffman, *Vortex Dynamics* (Cambridge: Cambridge University Press 1992), chap. 10; K. Shariff, A. Leonard, "Vortex Rings," *Annual Review of Fluid Mechanics* 24 (1992): 235-279; and respective references. For experiments and theory on propagation losses see: T. Maxworthy, "The structure and stability of vortex rings," *Journal of Fluid Mechanics* 51, no. 1 (1972): 15-32; T. Maxworthy, "Turbulent vortex rings," *Journal of Fluid Mechanics* 64, no. 2 (1974): 227-239; T. Maxworthy, "Some experimental studies of vortex rings," *Journal of Fluid Mechanics* 81, no. 3 (1977): 465-495.

139. For a few preliminary indications see: Altmann (note 1), section 5.1.3.

140. For some information on U.S. efforts at vortex-ring weapons, see G. Lucey, L. Jasper, "Vortex Ring Generators," in *Non-Lethal Defense III* (note 2), paper lucey.pdf; J. Dering, "High Energy Toroidal Vortex for Overlapping Civilian Law Enforcement and Military Police Operations" (ibid.), paper jd.pdf.

141. Tapscott/Atwal (note 19), p. 45.

142. Altmann (note 1), appendix A.7.

143. See e.g.: I. I. Glass, J. P. Sislian, *Nonstationary Flows and Shock Waves* (Oxford: Clarendon, 1994), chap. 12.

144. Tapscott/Atwal (note 19), p. 46.

145. Altmann (note 1), appendix A.7.

146. Lewer/Schofield (note 2), p. 12.

147. 5 mm/s is the threshold for "architectural" damage, and was discussed as safe limit for intermittent vibrations. Residential buildings in good condition should stand 10 mm/s. "Minor damage" occurs above 50-60 mm/s: A. C. Whiffin, D. R. Leonard, "A survey of traffic-induced vibrations," RRL Report LR 418 (Crowthorne Berkshire: Road Research Laboratory 1971), p. 14, table 4.

148. With grassy soil this maximum value occurs typically around several times ten Hz; at different frequencies, it may be 5-10-fold lower. See: J. M. Sabatier et al., "Acoustically induced seismic waves," *Journal of the Acoustical Society of America* 80, no. 2 (1986): 646-649; Altmann/Blumrich (note 80); W. Kaiser, *Sound and Vibration from Heavy Military Vehicles - Investigations of Frequency Assignment and Wave Spreading with respect to Monitoring under Disarmament Treaties* (Hagen: ISL, 1998).

149. "Non-lethal devices slice across science spectrum," *National Defense* (October 1993): 25, quoted after: Arkin (note 12).

150. Note that modern industrial buildings without plaster can stand earthquakes with soil vibrations of 20-40 mm/s: Whiffin/Leonard (note 147).

151. Lewer/Schofield (note 2), p. 12.

152. Vomiting: "Non-lethality ..." (note 2); Evancoe (note 18); Kiernan (note 16); Morehouse (note 2). Uncontrolled defecation or diarrhoea: Kiernan (note 16), Toffler/Toffler (note 12), p. 187; bowel spasms: "Non-lethality ..." (note 2); Morehouse (note 2).

153. High audio frequencies: Allen et al. 1948 (note 90); ultrasound: Parrack 1952 (note 91); H. O. Parrack, "Effect of Air-borne Ultrasound on Humans," *International Audiology* 5 (1966): 294-307; W. I. Acton, M. B. Carson, "Auditory and Subjective Effects of Airborne Noise from Industrial Infrasound Sources," *British Journal of industrial Medicine* 24 (1967): 297-304.

154. Dickson/Chadwick (note 63).

155. Parrack 1966 (note 153).

156. Mohr et al. (note 58).

157. E.g. with whole-body-exposed awake guinea pigs and monkeys: D. E. Parker, "Effects of Sound on the Vestibular System," ch. 7 in Tempest (note 53).

158. Gavreau et al. 1966 (note 54), p. 9.

159. Mohr et al. (note 58). Note that testicular aching (a different potentially embarrassing effect) of one subject was reported here.

160. See note 157.

161. Section 5.3 in: M. J. Griffin, *Handbook of Human Vibration* (London etc.: Academic, 1990).

162. Lumsden (note 13), p. 203.

163. Mohr et al. (note 58).

164. SARA (note 12). For *vibration*-induced gastrointestinal hemorrhages, on the other hand, see the sub-section on low-frequency vibration.